BOND STRENGTH AND MODULUS OF ELASTICITY OF ENGINEERED CEMENTITIOUS COMPOSITES

By

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ABSTRACT

The compressive strength of plain or conventional concrete is high, but plain concrete possesses a very low tensile strength, limited ductility and little resistance to cracking. New generations of concrete such as high strength concrete and ultra-high strength concrete have been successfully developed. Although these new generation concrete have extremely high compressive strength, their tensile strength, ductility and resistance to drying shrinkage cracking have not been significantly improved which limits their use for structural applications. All current methods to improve the ductility and tensile strength of concrete members such as the addition of discontinuous discrete fibers to concrete during mixing, the use of reinforcement steel bars and restraining techniques are not cost effective. Established literatures show that Engineered Cementitious Composites (ECC) exhibits ductile behavior under uniaxial tension load. ECC has been repeatedly reported by different researchers to be characterized by high ductility, tight crack width control and exhibition of pseudo-strain hardening behavior with several percent tensile strains as compared to brittle and quasi-brittle behaviors for plain concrete and Fiber-Reinforced Concrete (FRC) respectively. Thus, the objectives of this project are: 1) to develop polyvinyl alcohol (PVA) fiber reinforced self-consolidating ECC, 2) to investigate the bond strength between the developed PVA-ECC and reinforcement bars and 3) to determine the Modulus of Elasticity of the developed PVA-ECC. To achieve the above project objectives, the following activities were performed: mixing / casting, curing and testing of 100 mm x 100 mm x 100 mm ECC cubes and ECC cylinders of heights 200 mm and 300 mm with diameters 100 mm and 150 mm respectively. The tests conducted include slump flow, Visual Stability Index, V-funnel, L-box (for self-compacting concrete requirements), pull-out and modulus of elasticity tests. The values of slump flow, V-funnel and L-box measured in this project all satisfied the requirements for self-consolidating concrete (SCC). It has also been found out that the bond strength between reinforcing steel and ECC increases with increase in PVA fiber contents. The modulus of elasticity of PVA-ECC also increases with increasing PVA fiber content and increasing compressive strength of PVA-ECC.

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CHAPTER 1: INTRODUCTION

1.1. Background of the study

Concrete is the most widely used man made construction material in the world, and is second only to water as the most utilized substance on the planet (Gambhir, 2004). Conventional concrete or generally known as concrete is a mixture of cement, aggregates (coarse and fine aggregates) and water (and sometimes admixtures). Concrete with increasingly high compressive strength have been developed few decades ago, but because most of these high strength concrete developed remain brittle (have limited ductility) and have very low tensile strength and little resistance to cracking, thus their use for structural applications are being limited. Shetty (2001), pointed out that, the use of reinforcement steel bars and application of restraining techniques both improve the tensile strength of concrete members , but not the inherent tensile strength of the concrete itself. As a result, more and more researches have been conducted so as to improve the ductility as well as the tensile stress of concrete. Results from the conducted researches have shown that the addition of discontinuous discrete fibers to concrete during mixing can significantly improve the flexural strength, impact strength, toughness, fatigue strength and resistance to cracking (Kosmatka & Panarese, 1994). This type of concrete mix consisting of cement, sand, coarse aggregates, water and sometimes admixtures containing uniformly dispersed discrete fibers is called Fiber-Reinforced Concrete (FRC) and is primarily used in pavements, overlays, patching, hydraulic structures, thin shells and precast products (Kosmatka & Panarese, 1994). Several types of fibers including steel fibers, polyvinyl alcohol (PVA) fibers, polyproplyne (PP) fibers, glass fibers and so on have been successfully used in FRC.

Further effort made to modify the brittle behavior of plain cement has resulted in modern concepts of high performance fiber reinforced cementitious composites (HPFRCCs) that exhibit ductile behavior under uniaxial tension load. The resulting composite, which exhibits a pseudo-ductile behavior similar to that of steel, is called ‘‘engineered cementitious composites (ECC)” Zhang, Leung and Cheung, (2006). ECC is characterized by ultra-high tensile ductility and tight crack width control and ECC with 2% volume fraction of Poly-Vinyl Alcohol (PVA) fibers demonstrates a tensile strain capacity of 3–5%, which is two orders of magnitude higher than that of normal concrete and FRC (Li, et al, 2002). The high ductility of ECC is due to the tensile strain hardening behavior through multiple cracking mentioned earlier. Due to such high tensile ductility and tight crack width control, ECC exhibits superior durability compared to normal concrete and FRC under various mechanical and environmental conditions (Uddin, and Hirozo, 2007). The superior durability makes ECC a promising material to enhance safety, serviceability, and sustainability of civil infrastructure (Huang, et al, 2013).

In this project, a self-consolidating ECC with a compressive strength of 70 MPa or more will be developed and investigation will be focused on the rheological properties, compressive strength, bond strength and Modulus of Elasticity of the developed self-consolidating ECC.

1.2. Problem statement

1.2.1. Problem Identification

Plain or conventional concrete possess a very low tensile strength, limited ductility and little resistance to cracking. Internal micro cracks inherently present in concrete propagates due to the poor tensile strength of concrete which will eventually lead to bristle fracture of the concrete (Shetty, 2001). Current method to improve the tensile strength of concrete members is by the use of reinforcement steel bars and application of restraining techniques but such solution methods add up to the total cost of construction of concrete structures. ECC is a new innovative class of fiber reinforced cementitious composites characterized by high tensile strength, high ductility and tight crack width control with minimum fiber volume fraction of 2%. This experiment therefore, focuses at developing a self-consolidating PVA-ECC to address the problems of plain concrete which include: low tensile strength, limited ductility and little resistance to cracking.

1.2.2. Significant of the Project

This project involves the development of PVA fiber reinforced self-consolidating ECC. Self-compacting concrete (SCC) do not require vibration for placing and compaction but is able to flow under its own weight, completely filling formwork and achieving full compaction, even in the presence of congested reinforcement (Kosmatka & Panarese, 1994).The use of SCC shortens concrete construction time, lowers concrete construction costs by decreasing the labor and equipment needed on construction sites, improves working environment due to reduced noise pollution and injuries related to vibration work of concrete, makes it easier to concrete heavily congested structural elements and hard-to-reach areas, and results into a higher-quality finish surfaces and increased durability of concrete structures. As mentioned earlier, FRC has improved flexural strength, impact strength, toughness, fatigue strength and improved resistance to cracking. Therefore, incorporating PVA fiber into ECC in this project will help address the problems associated with plain concrete such as low flexural strength, low ductility and little resistance to drying shrinkage cracking which limits its' use in structural applications. ECC is effective in resisting tensile stress and thus changing the failure mode of concrete from brittle to ductile due to the tight crack width control. This can lead to improved structural performance of ECC members thus, maximizing the use of the material in structural application.

1.3. Objectives of the project

1. To develop polyvinyl alcohol (PVA) fiber reinforced self-consolidating Engineered Cementitious Composites (ECC).
2. To investigate the bond strength between the developed PVA-ECC and reinforcement bars.
3. To determine the Modulus of Elasticity of the developed PVA-ECC

1.4. Scope of Study

To achieve the objectives of this research:

The mix design or mix compositions of ECC are determined followed by the measurement of the quantities of each ingredient as shown in the mix proportions and then mixing the constituents: sand, cement, fly ash, PVA fibers, water and superplasticizer. Just after the mixing is competed, characteristic tests for self-compacting concrete especially slump flow, L-box and V-funnel are then conducted. The results for slump flow, L-box and V-funnel tests conducted are compared to the requirements for self-compacting concrete.

Once the requirements for SCC are fulfilled by the ECC, Six (6) 100 mm x 100 mm x 100 mm Cubes, are then cast for each of the five (5) mixes to be used for the determination of compressive strength of the ECC at the age of 7 days (3 cubes) and 28 days (3 cubes). 3 Cylinders of (ϕ=100mm and H=200mm) for each mix for Pull-Out Test test and 3 Cylinders of (ϕ=150mm and H=300mm) for each mix for Modulus of Elasticity. The experimental results obtained are then be analyzed and conclusions as well as recommendations for further work done based on the analysis of the results obtained.

1.5. The Relevancy of the Project

Normal concrete is used as a construction material all over the world due to its durability, resistance to fire, energy efficiency, and on-site fabrication. On the other hand, concrete has the disadvantages of low tensile strength, low ductility and little resistance to cracking, thus limiting its use for structural applications. Engineered cementitious composites (ECC) has superior ductility and tight crack width control. Since ECC is effective in resisting tensile stress and such a flexural performance of concrete is important for its applications in structures, it (ECC) can be an innovative and sustainable solution to the durability and serviceability problems associated with plain concrete. As a result, there is need to fully understand the rheological, mechanical and durability properties as well as the structural behaviors of this new generation of concrete hence the necessity of this project which aims at investigating the effects of fiber dosage in the rheological properties as well as the bond strength and modulus of elasticity of ECC.

1.6. Feasibility of the Project within the Scope and Time frame

All the tools and equipment required for this research are available in the UTP Concrete Laboratory (Lab), so all the project works such as casting, curing and testing can be done in the Lab. The materials required for the project can also be obtained just nearby. In terms of time, the research will be completed within 28 weeks with the first 14 weeks been utilized for material gathering, tools and equipment organization, literature review and expected methodology writing while the last 14 weeks focus on mixing/casting, testing, discussion of test results and preparation and submission of the necessary papers. The project is therefore feasible within the scope and time frame.

CHAPTER 2: LITERATURE REVIEW

2.1. Engineered Cementitious Composites (ECC)

The effort to modify the brittle behavior of plain concrete (PC) has resulted to the development of fiber reinforced concrete (FRC), and then ECC. Engineered cementitious composites (ECC) are a class of ultra-ductile fiber reinforced cementitious composites, characterized by high ductility and tight crack width control (Zhou et al, 2012). ECC exhibits tensile strain-hardening behavior through multiple micro-cracking with self-controlled crack width, leading to fracture toughness similar to aluminum alloys (Maalej, Hashida & Li, 1995). Even at large imposed deformation of several percent, crack widths of ECC remain small, less than 80 micron (Weimann & Li, 2003). Tensile strain capacity in the range of 3–5 % which is about 300–500 times that of plain concrete and fiber reinforced concrete (FRC), has been demonstrated in ECC materials using polyvinyl alcohol (PVA) fibers with fiber volume fraction at 2 % (Li & Li, 2012).

The material constituents of ECC are similar to that for fiber reinforced concrete (FRC) and include water, cement, sand, fiber, and superplasticizer but without coarse aggregates. According to Li & Kanda, (1998), coarse aggregates are not used because they tend to adversely affect the unique ductile behavior of the composite. Additionally, with the presence of PVA fibers in ECC, aggregates with size larger than average fiber spacing can cause fiber clumping and poor fiber dispersion (Huang, et al, 2013). Huang, et al, (2013), also mentioned that fiber clumping becomes more pronounced with increase in aggregate size.

Poor fiber dispersion leads to a reduction in the number of effective fibers at the failure crack, which causes a decrease in tensile strength and tensile strain capacity (Li & Li, 2012). According to Huang, et al, (2013), it is therefore, necessary to use fine aggregate in the design of ECC so as to maintain low fracture toughness of the matrix and to maintain uniform fiber dispersion in the composite, both of which are crucial for achieving good tensile performance of ECC. Due to the above considerations, micro-silica sand (SS) with an average diameter of approximately 110 micron is frequently used in various ECC compositions (Huang, et al, 2013).

Another means to obtain a uniform fiber distribution is by controlling the plastic viscosity of the ECC mortar before adding fibers, for example, by adjusting water-to-powder ratio or chemical admixtures but such adjustments have some limitations and may result in poor mechanical properties of ECC (Zhou et al, 2012). Zhou et al, (2012), therefore, proposed an innovative approach to improve the fiber distribution of ECC by adjusting the standard mixing sequence.

The standard mixing sequence for any fiber reinforced concrete consists of adding the fibers only after all solid and liquid materials are mixed but undesirable plastic viscosity before the fiber addition may cause poor fiber distribution in the matrix which can result into poor hardened properties. In the adjusted mixing sequence proposed by Zhou et al, (2012), the mixing of the solid materials with the liquid material is divided into two steps and the addition of fibers is between the two steps. The adjusted mixing sequence therefore involves adding and mixing part of the water with solid materials and superplasticizer at low speed for 1 min and then at high speed for 2 min followed by the addition of PVA fibers and mixed at high speed for 2 min. After the fibers are mixed homogenously, the rest of water and superplasticizer were added and mixed at high speed for another 2 min. Zhou et al, (2012), then compared the experimental results of the uniaxial tensile test and the fiber distribution analysis of the standard mixing sequence with that of the adjusted mixing sequence and found out that the adjusted mixing sequence increases both the tensile strain capacity and ultimate tensile strength of ECC and improves the fiber distribution.

The type of fiber mainly used in ECC is Poly Vinyl Alcohol (PVA) fiber, but several other types of fibers such as steel fibers, polyethylene fibers just a few to mention have also been successfully used to produce ECC of the desired rheological and mechanical properties. The polyvinyl alcohol (PVA) fiber with a diameter of 39 micron and a length of 6 mm to 12 mm is often used (Zhou et al, 2012). Sahmaran & Li, (2008), also pointed out that the high tensile ductility of ECC can be achieved with a typically moderate fiber volume fraction of 2% by volume.

Figure 2.1 shows the general features of the uniaxial tensile stress-strain relation of PC, ordinary FRC and ECC (Lin and Li, 1997). It shows that as compared to brittle and quasi-brittle behaviors for PC and FRC respectively, ECC exhibit pseudo-strain hardening behavior with several percent tensile strains (Shimizu et al, 2004). This behavior is characterized by a more ductile post-peak softening in uniaxial tension compared with the plain matrix, as a result of gradual fiber pull-out from a single crack plane. The pseudo strain-hardening behavior of fiber reinforced engineered cementitious composites (ECC) is a desirable characteristic for it to act as a substitute for concrete to suppress brittle failure (Zhang, Leung and Cheung, 2006). As schematically shown in Figure 2.2, three typical deformation stages namely, elastic deformation, multiple cracking and damage localization are associated with a uniaxial tensile stress-strain relation of a strain-hardening cementitious composite or ECC (Lin and Li, 1997).

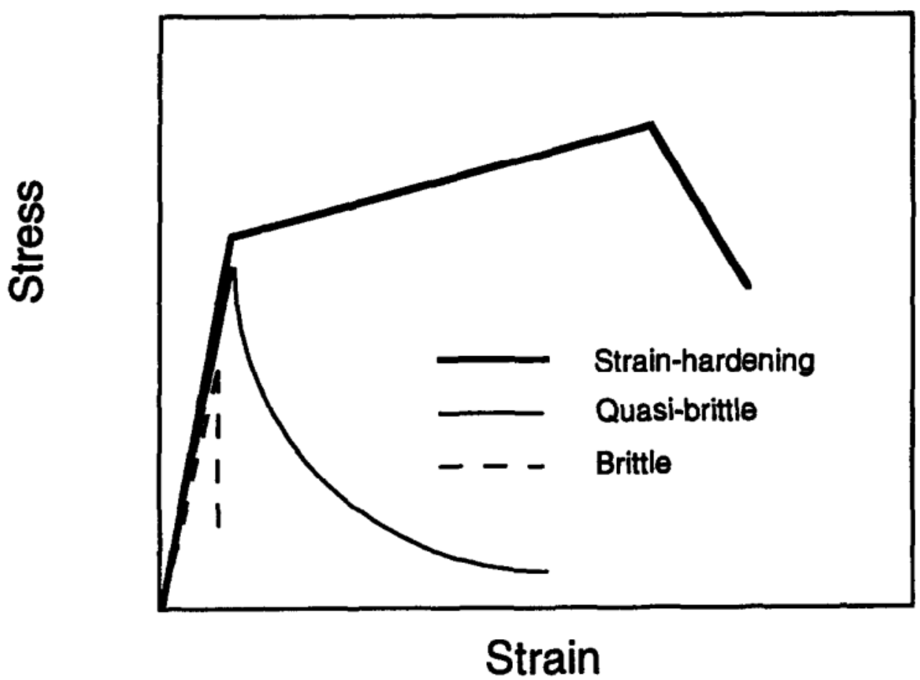


Figure 2.1: Uniaxial tensile stress-strain curves for brittle (PC), quasi-brittle (FRC) and strain-hardening cementitious materials (ECC), (Lin and Li, 1997).

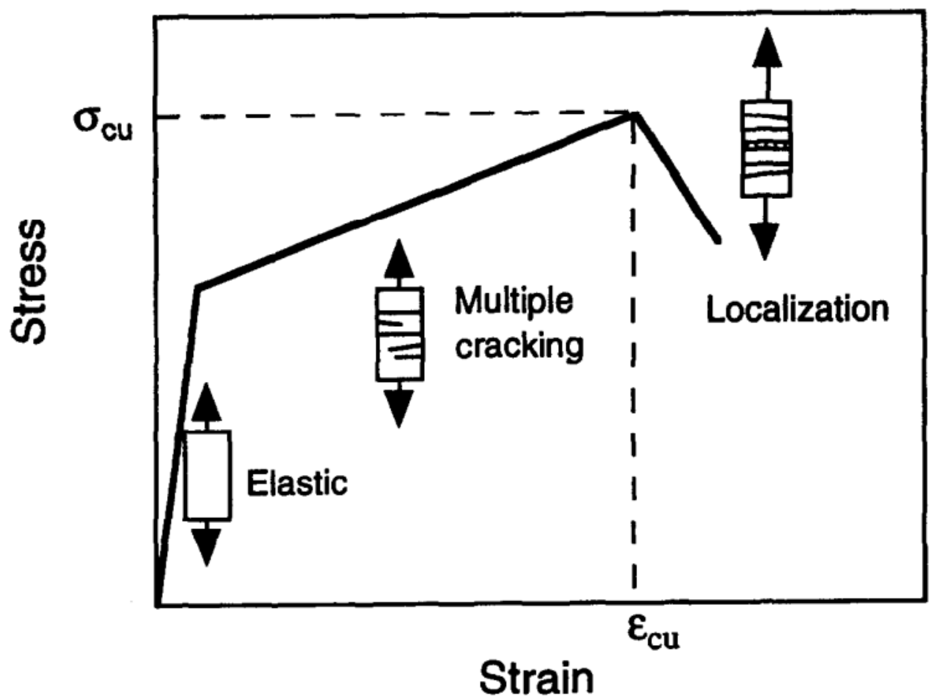


Figure 2.2: Three deformation stages of ECC during a uniaxial tensile test (Lin and Li, 1997).

2.2. Bond Strength of Concrete (Pull-Out Test)

Warner et al, (1998), pointed out that structural concrete functions effectively as a composite material because the reinforcement is bonded to the surrounding concrete. Bond ensures that there is little or no slip of the steel relative to the concrete and hence allows local forces to be transferred across the steel-concrete interface. The bond action between concrete and reinforcing steel is due to chemical adhesion, mechanical friction and bearing of the concrete against the deformations and surface irregularities on the bar. If plain reinforcement bars are used however, the bond will be due to adhesion and friction only.

The bond strength (also known as pull-out strength) of hardened concrete is determined by measuring the force required to pull a reinforcing bar embedded in to the concrete. According to Warner et al, (1998), the bond strength depends on the embedded length L, the bar size and the strength of the concrete in which the bar is cast. Bond failure occurs in the case of deformed bars by longitudinal split of the concrete, pull out may occur if a plain steel is used and breaking strength of the bar may be developed if the embedded length L is long enough (Warner et al, 1998).

According to the provisions of ACI 318 the embedded length of reinforcing bar for sufficient anchorage is inversely proportioned to the square root of the compressive strength, implying that the bond strength should be linearly proportional to square root of compressive strength.

Asl, Dilmaghani and Famili (2008), conducted an experiment to investigate the bond between self- compacting concrete (SCC) and steel reinforcement (Rebar) and that between normal concrete (NC) and reinforcement bars. The three researchers measured the ultimate bond strengths at various ages for both SCC and NC by carrying out pull-out tests and then converting the pull-out loads into bond stresses using a formula below that is based on the embedment length and reinforcing bar perimeter.

$$\tau = \frac{p}{\pi d l}$$

Where

- **p** refers to the applied load,
- **d** is the bar diameter and
- **l** is the embedment length.

Their experimental results showed that SCC specimens had higher bond to reinforcing bars than normal concrete specimens and they found a more consistent correlation between bond strength and compressive strength of NC.

Helincks, et all, (2013); carried out an experimental test program to investigate the bond and shear performance of powder-type self-compacting concrete (SCC). In order to examine the bond strength of reinforcement in concrete, they performed pull-out tests on 72 specimens cast with different concrete mixtures and rebar diameters of 8, 12, 16, and 20 mm (according to RILEM recommendation RC6 part 2) were performed. Their experimental test results show that bond strength of the SCC increases as the bar diameter increases until a certain optimum diameter. The researchers measured larger bond strengths for bars with diameter 12 and 16 mm but also noticed a decrease in bond performance with larger diameter bars (20 mm diameter bars).

Sfikas and Trezos, (2013); on the other hand, investigated the effect of composition variations on bond properties of Self-Compacting concrete (SCC) and Normally Vibrated Concrete (NVC) specimens, and found out that bond stresses, decrease linearly for higher water content and higher silica fume replacement levels. Their test results also showed that SCC develops an improved bond capacity compared to same strength NVC with similar composition. Another important finding of the study is that most SCC mixtures present a low variability of the bond stress, compared to the considerably higher variability for NVC mixtures especially when compared to SCC mixtures with higher w/b ratios or silica fume levels.

Bouazaoui, and Li, (2008); performed an analysis of steel/concrete interfacial shear stress by means of pull out test and concluded that:

- The ultimate load (pull-out force) F_{max} increases according to the embedded length of steel in concrete and the increase are very linear.
- It can be observed that for a constant length L, embedded in concrete, the increase in force is also linear according to the steel rod diameter.
- Comparison between the steel/concrete specimens with adhesive joint and without adhesive joint revealed that the ultimate load increased significantly for the structure having an adhesive in the joint.

Based on the last finding of Bouazaoui, and Li, (2008) above, it can be concluded that; the role of adhesive joint to increase the adhesive strength between the steel surface and the concrete surface is considerable.

Furthermore, an experiment to investigate the effect of steel wrapping jackets on the bond strength of concrete and the lateral performance of circular RC columns was conducted by Choi, et all, (2013). It was found out that the jackets increased the bond strength and ductile behavior due to the transfer of splitting bonding failure to pull-out bonding failure.

The principle of the pull-out test

The pull-out test is conducted by applying a tensile force to the protruding or un embedded end reinforcement bar (Figure 2.3). The force is applied by hydraulic jack and a rigid steel plate needs to be placed between the test specimen and the hydraulic jack to act as a bearing plate and to ensure that the force is being applied perpendicularly to the face of the concrete surface (Sfikas and Trezos, 2013). The load is then applied and increased at a steady rate of (0.5 ± 0.2) kN/s without shock until fracture occurs (BSI BS EN 12504-3, 2005).

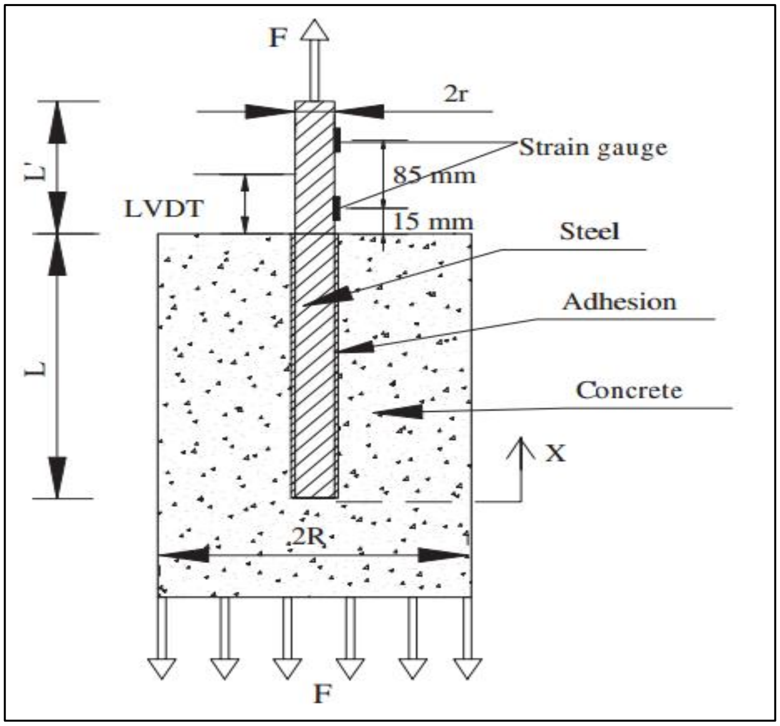


Figure 2.3: Description of the principle of pull-out tests (Bouazaoui, and Li, 2008).

2.3. Modulus of Elasticity of Concrete

Modulus of elasticity is an important parameter used for the structural assessment and retrofitting of concrete structures (Yildirim and Sengul, 2011). It is also stated clearly in ASTM C469 / C469M – 10 that, “the modulus of elasticity and Poisson's ratio values, applicable within the customary working stress range (0 to 40 % of ultimate concrete strength), are used in sizing of reinforced and non-reinforced structural members, establishing the quantity of reinforcement, and computing stress for observed strains. According to Sideris, Manita, and Sideris, (2004), the value of the modulus of elasticity of concrete depends on the values of modulus of elasticity of paste and modulus of elasticity of aggregates.

Yildirim and Sengul, (2011), conducted an experimental investigation on the modulus of elasticity of substandard and normal concretes. To obtain substandard concretes, they substantially increased the water/cement ratios and as a result reduced the compressive strengths down to 4 MPa. From the experiment, it was found out that:

a) The modulus of elasticity of concrete decreased with the increase in the water/cement ratio.
b) The modulus of elasticity is not affected substantially with the use of fly ash except at the fly ash content of 33% whereby the modulus of elasticity of the mixture produced with water/cement ratio of 0.75 is higher than that of the reference mixtures.
c) The modulus of elasticity of the concretes produced using different types of aggregates: dolomite, basalt and quartz were almost the same
d) The modulus of elasticity increases with compressive strength as expected.

The modulus of elasticity of concrete decreased with the increase in the water/cement ratio because when the water/cement ratio is increased, capillary porosity of concrete also increases and the aggregate–cement paste interface therefore becomes more porous and micro-cracking at this interfacial zone can take place much more easily, and as a result, lower modulus of elasticity is obtained (Yildirim and Sengul, 2011).

On the other hand, at lower water/cement ratios, the interface between the aggregate and cement paste is stronger and the ascending branch of the stress–strain relation-ship is more linear for increasing stress values. In such high strength concretes, cracks formed in the cement paste can go through the aggregate and as a result, properties of aggregates play a more important role in the modulus of elasticity obtained (Yildirim and Sengul, 2011).

According to Yildirim and Sengul, (2011), as the compressive strength of concrete increases, both the cement paste matrix and the interface becomes denser and stronger, and also better matching of the elastic properties of cement paste matrix and aggregate results in higher modulus of elasticity of concrete.

Sarıdemir, (2013), carried out an experiment to investigate the effects of silica fume (SF) and ground pumice (GP) on compressive strength and modulus of elasticity (E_c) of high strength concrete and found out that the modulus of elasticity of 150 x 300 mm concrete cylinder containing SF, GP and SF together with GP (apart from concrete containing 20% and 25% GP) were higher than the modulus of elasticity of the corresponding control mixture at 28 days. It was also found out that, the E_c of concrete containing SF is slightly higher than the E_c of concrete containing only GP and control mixture. Best fit linear relationship between modulus of elasticity and compressive strength obtained from the regression analysis of the experimental results is as illustrated in figure

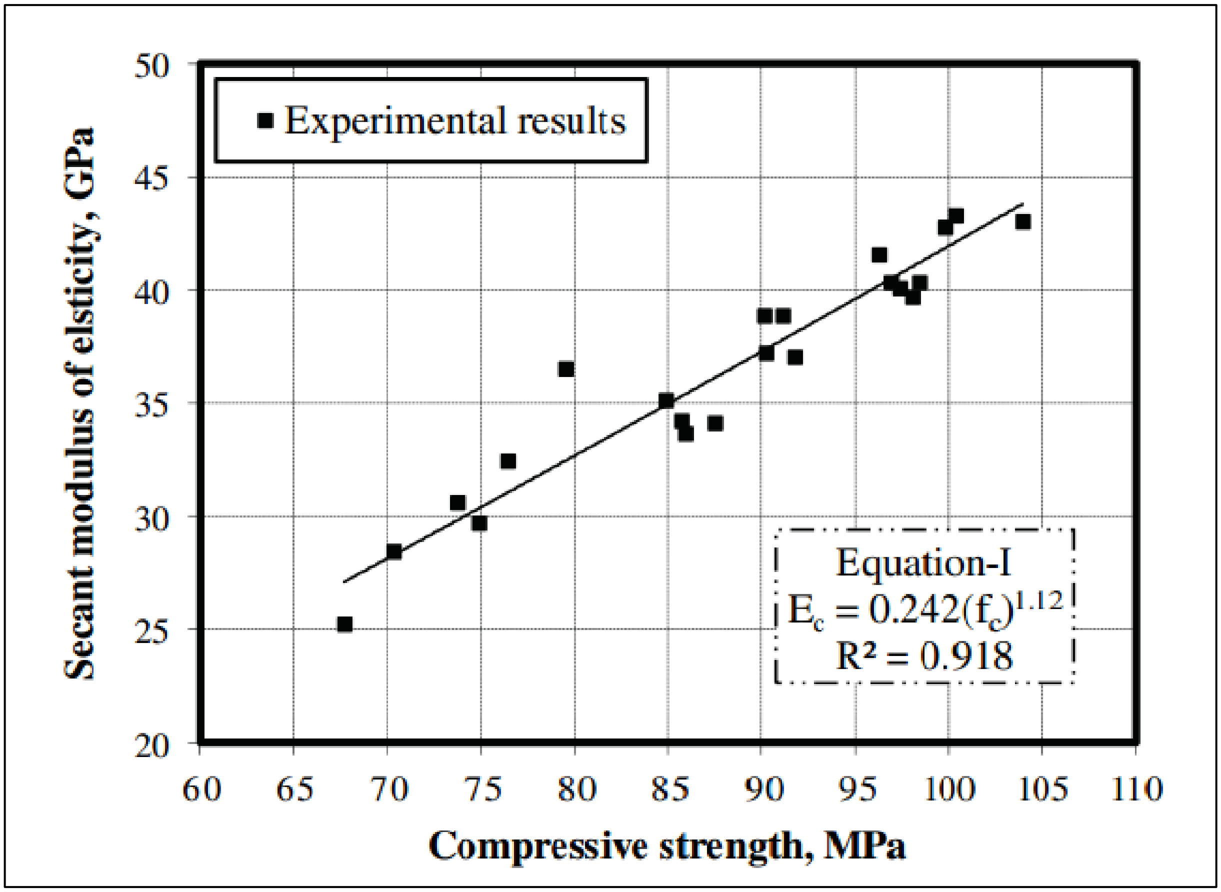


Figure: Relationship between modulus of elasticity and compressive strength, (Saridemir, 2013).

The modulus of elasticity of concrete E_c adopted in modified form by the ACI Code can be calculated by the formula given below:

$E_c = 0.043 w_c^{1.5} f_c^{0.5}$

Where

E_c = modulus of elasticity of concrete (MPa) and

f_c = 28 days compressive strength of concrete (MPa)

With normal weight and normal density concrete, the above relationship can be simplified to

$Ec = 4700 f_c^{0.5}$

CHAPTER 3: RESEARCH METHODOLOGY

3.1. Materials

The materials used in this project include:

1. An ordinary Portland cement (OPC) with chemical compositions shown in Table 3.1
2. Fly Ash (FA) with chemical compositions also summarized in Table 3.1 but a detail of the spectrograph and all detected elements in the three samples of the FA is provided in Appendix 1.
3. Sand passing 320 mm sieve
4. PVA fiber of length 12 mm and diameter, 39 micron
5. A Polycarboxylate based Superplasticizer with a solid content of 35.7% to improve flow ability.
6. Clean mixing water

Table 3.1: Chemical Compositions of OPC and FA

Chemical Composition	**Percentage (%)**	
	OPC	**Fly Ass**
SiO_2	20.3	43.25
Al_2O_3	4.2	20.59
Fe_2O_3	3	12.49
CaO	62	11.11
MgO	2.8	3.76
SO_3	3.5	1.45
K_2O	0.9	1.96
Na_2O	0.2	0.9

3.2. Project activities

3.2.1. Mix Design

Achieving Self-Consolidating ECC and with better hardened properties such as high compressive and tensile strengths as well as improved ductility and tight crack control entirely depend on the mix compositions of ECC. For this project, a water/binder ratio of 0.15 and water/cement ratio of 0.32 are used. The mix proportions of the matrices are shown in Table 3.2.

Table 3.2: Mix Compositions for Engineered Cementitious Composites

Mix ID	Water/ Binder ratio	Water/ Cement ratio	OPC (kg/m^3)	Sand (kg/m^3)	Fly Ash (kg/m^3)	Water (kg/m^3)	PVA (kg/m^3)	Super-plasticizer
Mix Group 1								
M_1	0.15	0.32	583	467	700	187	26 (2.0%)	9.5
M_2	0.15	0.32	583	467	700	187	32 (2.5%)	9.5
M_3	0.15	0.32	583	467	700	187	38 (3.0%)	9.5
M_4	0.15	0.32	583	467	700	187	45 (3.5%)	9.5
M_5	0.15	0.32	583	467	700	187	51 (4.0%)	9.5
Mix Group II								
N_1	0.15	0.32	583	467	700	187	-	4.5
N_2	0.15	0.32	583	467	700	187	13 (1.0%)	4.5
N_3	0.15	0.32	583	467	700	187	19 (1.5%)	4.5
N_4	0.15	0.32	583	467	700	187	58 (4.5%)	9.5
N_5	0.15	0.32	583	467	700	187	64 (5.0%)	9.5
Key: OPC = Ordinary Portland Cement, PVA = Poly Vinyl Alcohol Fiber								

3.2.2. Sample Preparation, Mixing/Casting and Curing

After coming up with the mix design, quantities of each ingredients as shown in the mix proportions are measured and the constituents: sand, cement, fly ash and PVA fibers were mixed for 2 minutes in a Hobart mixer. Half of the Water and super plasticizers are then added and mixed for 3 more minutes. Visual inspection is then carried out to ensure that the fibers are uniformly distributed. The remaining quantity of water and dosage of superplasticizers are then added and the mixing is continued for 3 minutes. The total duration of mixing is therefore 8 minutes.

Six (6) 100 mm x 100 mm x 100 mm Cubes, are then cast for each of the ten (10) mixes to be used for the determination of compressive strength of the ECC at the age of 7 days (3 cubes) and 28 days (3 cubes). The casting and testing schedule for the cubes is summarized in (Table 3.3). Other castings for this project as summarized in (Table 3.4) consist of:

- 3 Cylinders of diameter, ϕ =100mm and height, H=200mm) with 12 mm and 16 mm Steel Bars of embedded length 150 mm cast in for each Mix for Bond Strength test
- 3 Cylinders of diameter, ϕ =150mm and height, H=300mm) for each mix for test of Modulus of Elasticity.

Removal of each cast sample from the moulds is done after 24 hours and the samples are the placed in curing tank. Curing is continued until the testing date for each sample which is at 7 and 28 days for cubes (compressive strength test) and at 28 days for bond strength and Modulus of Elasticity). On the test date, the samples are removed from the curing tank, their surfaces are dried and their weight taken for determination of density. The samples are then tested and the test results tabulated as shown in the result and discussion chapter in this report.

Table 3.3: Mixing / Casting and testing Schedule for 100 mm x 100 mm x 100 mm cubes for compressive strength test

Mix ID	**Mixing / Casting Date**	**Testing Date**	
		7 days	**28 day**
M_1	4/10/2013	11/10/2013	1/11/2013
M_2	4/10/2013	11/10/2013	1/11/2013
M_3	10/10/2013	17/10/2013	7/11/2013
M_4	10/10/2013	17/10/2013	7/11/2013
M_5	11/10/2013	18/10/2013	8/11/2013
N_1	23/11/2013	7/12/2013	21/12/2013
N_2	23/11/2013	7/12/2013	21/12/2013
N_3	23/11/2013	7/12/2013	21/12/2013
N_4	23/11/2013	7/12/2013	21/12/2013
N_5	23/11/2013	7/12/2013	21/12/2013

Table 3.4: Mixing / Casting and testing Schedule for modulus of elasticity and bond strength tests

Mix ID	Mixing / Casting Date	Testing Date (28 day)	Sample Description
M_1	28/ 10 /2013	25/ 11 /2013	**a)** 3 Cylinders of (ϕ =150mm and H=300mm) for each Mix for Modulus of Elasticity and Poison's Ratio **b)** 3 Cylinders of (ϕ =100mm and H=200mm) with 12mm Steel Bar of embedded length 150 mm for each Mix for Bond Strength **Key:** H = Height and ϕ = Diameter
M_2	31/ 10 /2013	28/ 11 /2013	
M_3	01/ 11 /2013	29/ 11 /2013	
M_4	04/ 11 /2013	02/ 12 /2013	
M_5	29/ 10 /2013	26/ 11 /2013	
N_1	23/11/2013	21/12/2013	
N_2	23/11/2013	21/12/2013	
N_3	23/11/2013	21/12/2013	
N_4	23/11/2013	21/12/2013	
N_5	23/11/2013	21/12/2013	

3.2.3. Testing Program

Characteristic tests for self-compacting concrete

Four different tests were carried out to determine the fresh properties and to evaluate the rheological behavior of the self-consolidating PVA-ECC mixtures. The workability (unconfined flowability) of the PVA_ECC mixes was assessed by the Slump-flow test that was conducted in accordance with EN 12350-8:2010. Figure 3.1 illustrates the testing principle of the slump flow. The method of the Fresh Visual Stability Index

(VSI), as described by ASTM C1611-07, was used for the evaluation of the segregation tendency of the mixtures (Table 3.5). The passing ability was tested by the V-Funnel test and the L-Box test, according to EN 12350-9:2010 and EN 12350-10:2010 respectively. The results for slump flow, L-box and V-funnel tests conducted are compared to the requirements for self-compacting concrete summarized in Table 3.6 (EFNARC, 2002).

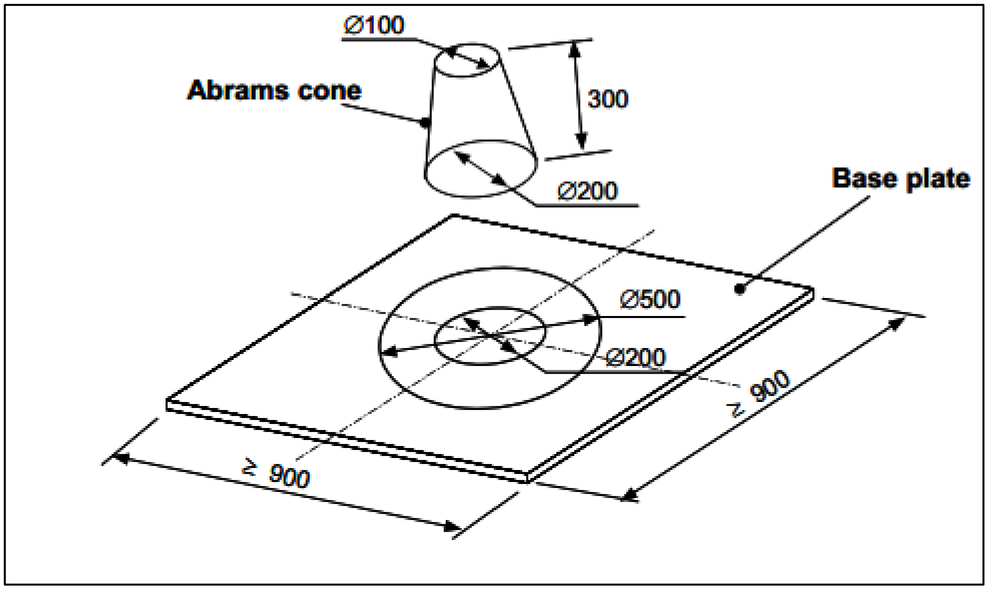


Figure 3.1: Testing Principle of slump flow using Abraham's Cone (EFNARC, 2002).

Table 3.5: Visual Stability Index Ratings (ASTM C 1611)

VSI	Criteria
0 = Highly Stable	No evidence of segregation or bleeding
1 = Stable	No evidence of segregation and slight bleeding observed as a sheen on the concrete mass
2 = Unstable	A slight mortar halo ≤0.5 in. and/or aggregate pile in the concrete mass.
3 = Highly Unstable	Clearly segregation by evidence of a large mortar halo > 0.5 in. and/or a large aggregate pile in the center of the concrete mass.

Table 3.6: Testing for workability or Requirements for Self-Compacting Concrete (EFNARC, 2002)

Test Method	**Property**	**Units**	**Application**		**Typical range of values**	
			Lab (Mix design)	**Field (QC)**	**Min.**	**Max.**
Slump-flow by Abrams cone	Filling ability	mm	✓	✓	650	800
T_{50cm} slump flow	Filling ability	sec	✓	✓	2	5
V-funnel	Filling ability	Sec	✓	✓	6	12
V-funnel at T_{5min}	Segregation resistance	Sec	✓	✓	0	+3
L-box	Passing ability	(h2/h1)	✓		0.8	1.0

The Pull-out test

The bond properties of reinforcement bars embedded in PVA fiber reinforced SCC-ECC is investigated in this experiment by conducting direct pull-out test of the reinforcement bars embedded in the PVA fiber reinforced SCC-ECC specimens and in SCC-ECC specimen without fibers and the results are then compared. Reinforcement bars with diameters of 12 and 16 mm cast in concrete cylinders of 100 mm diameter and 200 mm height are used for all mixtures, and the pull-out test was conducted based on BSI BS EN 12504-3 and RILEM recommendation RC6 part 2. The pull-out test was conducted using a 250 kN tensile test machine. During the testing, each pull-out test specimen was clamped in the testing device one at a time, a force of 5 kN is then applied on the specimen to obtain a good grip of the claw, after which the test continues at a constant rate of 0.02 mm/s and/or 0.5 kN/s. Figure 3.2 shows the set-up for the pull-out test.

Figure 3.2: Set-up for the pull-out test.

Test for Modulus of Elasticity

Figure 3.3: Testing for the Modulus of Elasticity of PVA-ECC cylinders.

Three cylinders, 150 mm in diameter and 300 mm in height, were used for the determination of the modulus of elasticity of self-consolidating PVA-ECC for each mix. The test was conducted according to ASTM C 469. The specimens were tested in uniaxial compression at a constant rate of loading 3.5 kN/s. Before testing, strain gauge is glued to the cylinder and then connected to the computer which reads the deformation in the concrete in micrometer per meter. Figure 3.3 shows the testing principle of Modulus of Elasticity. The method used for the execution of this project work is as summarized in Figure 3.2. More information and photos of project activities taken is included in Appendix 2.

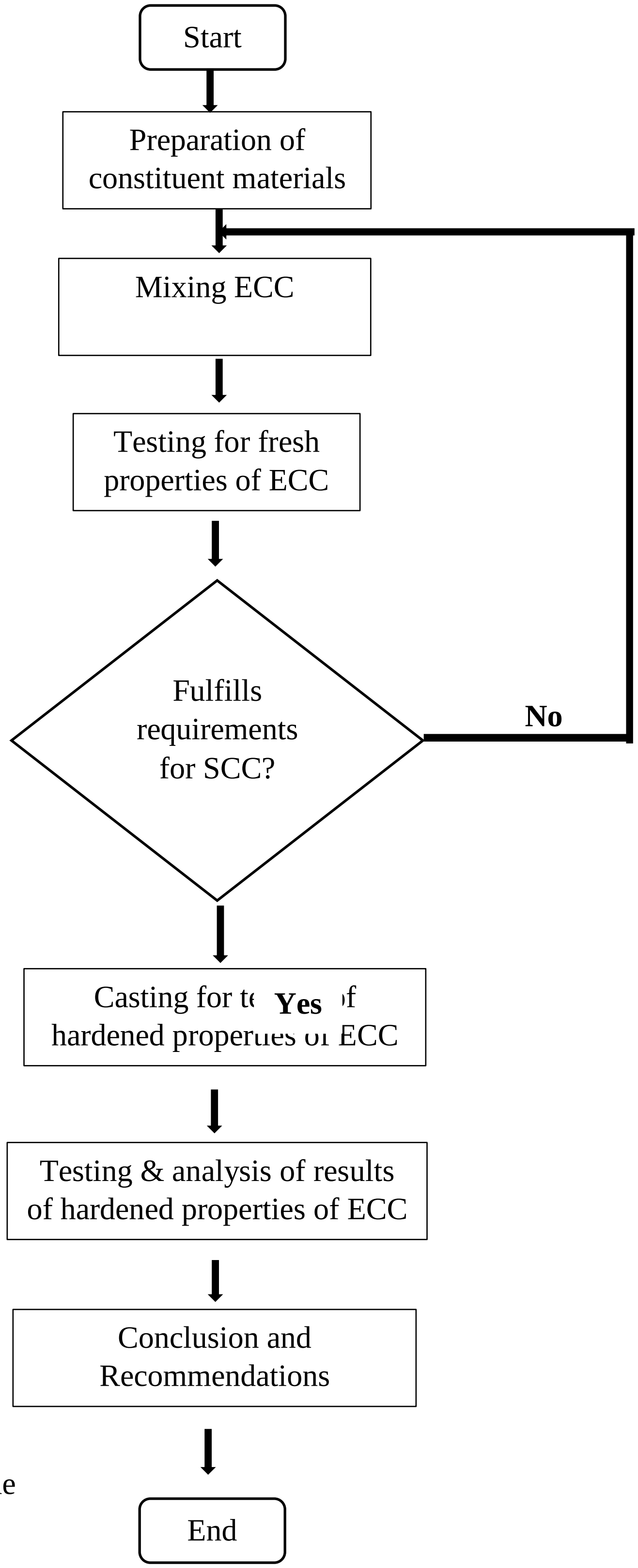


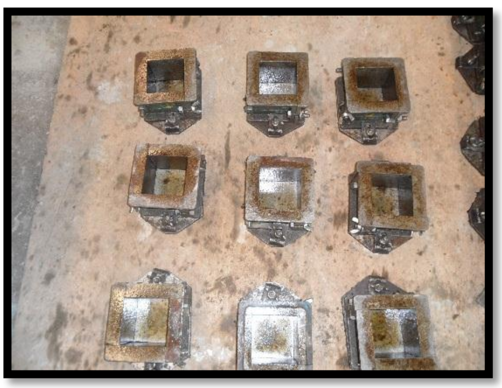
Figure 3.2: Summary of the project methodology

3.3. Tools, equipment and hardware required

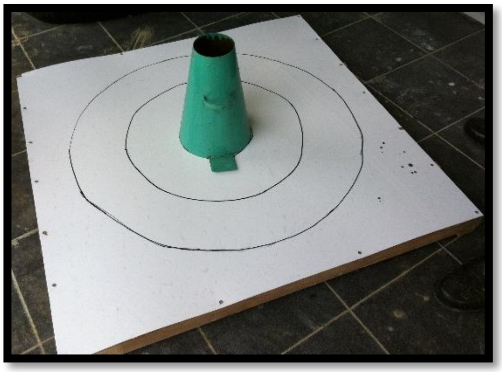
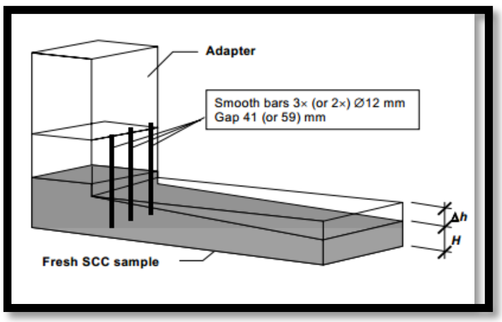
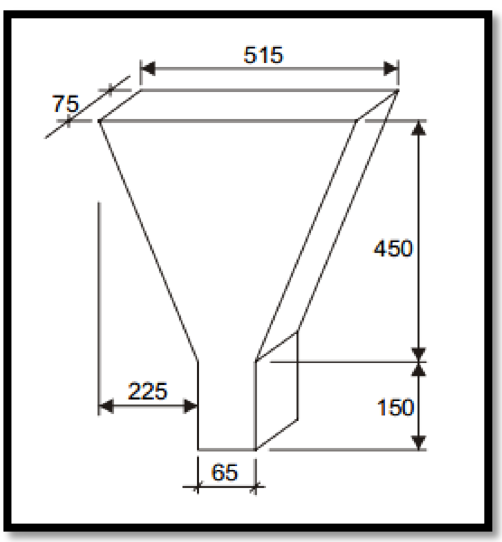
To effectively carry out the necessary activities for this project from mix design to the testing of the properties of both fresh and hardened fiber reinforced self-consolidating concrete, the tools or machineries and equipment in (Table 3.7) are needed.

Table 3.7: Tools, equipment and hardware required

Equipment	**Name and Function**
	Weighing machine for measuring the quantities or proportions of the constituents of ECC
	Measuring cylinder and beaker for measuring the quantity of superplasticizer required to achieve self-consolidating ECC and measuring the required quantity of water

	Concrete mixer for mixing constituents of ECC
	Concrete cube moulds of 100 mm x 100 mm x 100 mm for casting ECC cubes for 7, 28 and 60 days compressive strength test

	• Concrete beam moulds of 500 mm x 100 mm x 100 mm for casting ECC beams for 28 days flexural strength test • Concrete cylindrical moulds of 150 mm diameter and 300 mm height for Splitting Tensile test and test for Modulus of Elasticity and Poison's Ratio • Concrete cylindrical moulds of 100 mm diameter and 200 mm height with 12 mm diameter steel bars each cut 800 mm long for Bond Strength test
	Curing tank for curing the ECC

	1 m x 1 m base plate, Abrams cone and T_{50cm} slump flow test apparatus for measuring filling ability which as a requirements for SCC
	L-Box for measuring Passing ability which is one of the requirements for SCC
	V-Funnel for measuring filling ability which as a requirements for SCC

	Compressive strength testing machine to determine the compressive strength of concrete cubes at the ages of 7, 14 and 28 days
	Gotech universal testing machine GT-7001-LS20 for Pull-out test

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Testing for the requirements of SCC

The results of testing for SCC requirements are presented in (Table 4.1).

Table 4.1: Testing for SCC Requirements

Mix ID	Slump Flow				VSI	V - Funnel	L - Box		
	d_{max} (mm)	d_{perp} (mm)	S (mm)	T_{50}		t_v (sec.)	h_1 (mm)	h_2 (mm)	h2/h1
M_1	867	790	830	3	0	7	102	94	0.92
M_2	825	752	790	3	0	8	100	91	0.91
M_3	800	680	740	4	0	11	98	92	0.94
M_4	750	640	695	5	0	12	93	86	0.92
M_5	705	640	670	5	0	12	100	94	0.94
N_1	840	782	811	2	0	6	104	98	0.94
N_2	836	763	790	2	0	6	101	95	0.94
N_3	822	755	789	3	0	7	97	89	0.92
N_4	683	632	658	5	0	12	100	86	0.86
N_5	671	629	650	5	0	12	105	85	0.81
Note: The slump spread, $S = \frac{dmax + dperp}{2}$ to the nearest 5 mm									

Comparing the values obtained with the standard values for the requirement of SCC in Table 3.6 shows that, all the mixes have satisfied the requirements of SCC. All the measured values of the slump spread fall within the minimum (650 mm) and maximum (800 mm) requirement for slump spread of SCC except for mixes M_1. The slump flow for M_1 is 830 mm which exceeds the maximum requirement for SCC. The values of T_{50}

obtained are all in the range of 2 – 5 seconds required for SCC. The required V-funnel flow time for SCC as shown in Table 3.6 is 6 – 12 seconds and the ones obtained in this project all fall in this range for all mixes. The requirement for L-box (h_2/h_1) which is 0.8 – 1.0 have also been satisfied by all the mixes as shown in Table 4.1. Visual Stability Index Ratings of zero (VSI = 0) has been assigned for all mixes because there was no evidence of segregation or bleeding, so all the PVA-ECC mixes developed are highly stable. Assignment of the Visual Stability Index was based on the ratings of (ASTM C 1611). It can therefore, be concluded that the first objective of this research has been achieved thus; the PVA fiber reinforced ECC developed is self-consolidating. The test results for the fresh PVA-ECC show that slump spread decreases with increase in the content of PVA when other compositions remain constant. Furthermore, the V-Funnel flow decreases with increase in PVA content. The workability of the PVA-ECC is reduced at high percentage of PVA as illustrated by the plot of slump flow against PVA dosage (Figure 4.1). The slump flow is the maximum without PVA and as PVA dose increases, the slump spread decreases. The further increase of slump spread at 2.0% PVA is due to an increase in the amount of superplasticizer from 4.5 % to 9.5%.

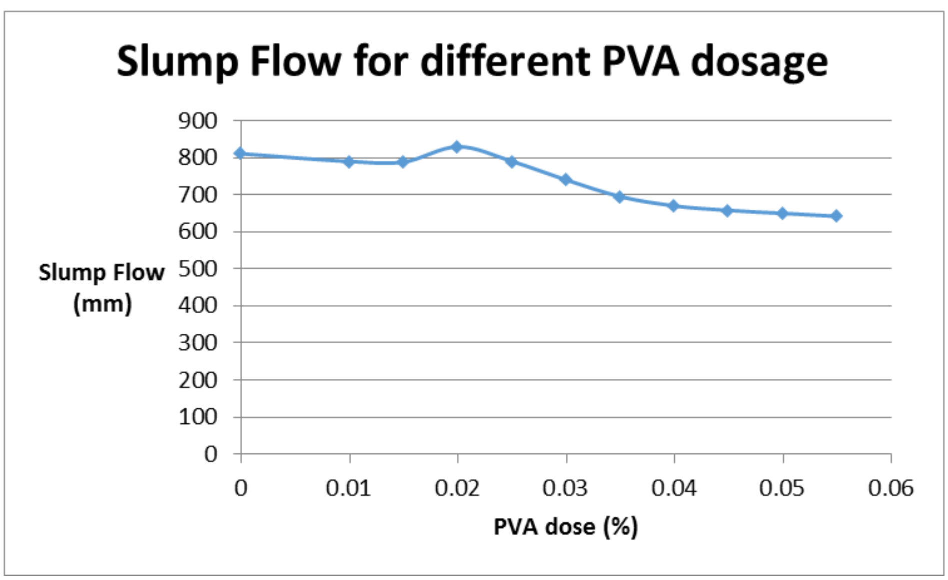


Figure 4.1: Slump Flow verses dose of PVA

4.2. Compressive strength of the ECC cubes

The results for the compressive strength of the cubes at the age of 7 days and 28 days are presented in (Table 4.2). For each of the ten mixes, six cubes were cast. Three cubes from each mix are used to determine the compressive strength of the developed ECC at the age of 7 and 28 days and the average value of the compressive strength for each age is recorded (Table 4.2).

Compressive strength test results from cast ECC cubes is used for quality control and for acceptance of the ECC. The test at 7 days may help detect any potential problems with the ECC quality but it is not the basis for rejecting the ECC, rejection can only be made if the specified or target strength at the age of 28 days is not meet.

As shown in Table 4.2, and Figures 4.3 & 4.4, the compressive strength of ECC increases with age just like that for plain concrete or FRC. Like in established literatures, much of the compressive strength of the ECC has already been attained at the age of 7 days. The strength for each mix is found to have increased after the age of 28 days but the increase is not much, so the attainment of compressive strength of ECC is similar to that of plain concrete and FRC but then the value of the strength is much higher. For this project, the target strength at 7 and 28 days are 38 MPa and 50 Mpa respectively and the values obtained for each mix much exceeded the target strength at both ages, so in terms of strength, the project’s target strength is met.

Table 4.2: Average compressive strength of ECC cubes at 7 and 28 days.

Mix ID	Average Compressive Strength (MPa)	
	7 days	28 days
M_1	85.20	95.53
M_2	76.70	91.88
M_3	74.40	97.74
M_4	71.60	96.47
M_5	71.10	90.59
N_1	90.50	103.50
N_2	90.00	103.42
N_3	89.90	109.00
N_4	70.80	89.93
N_5	70.32	84.89

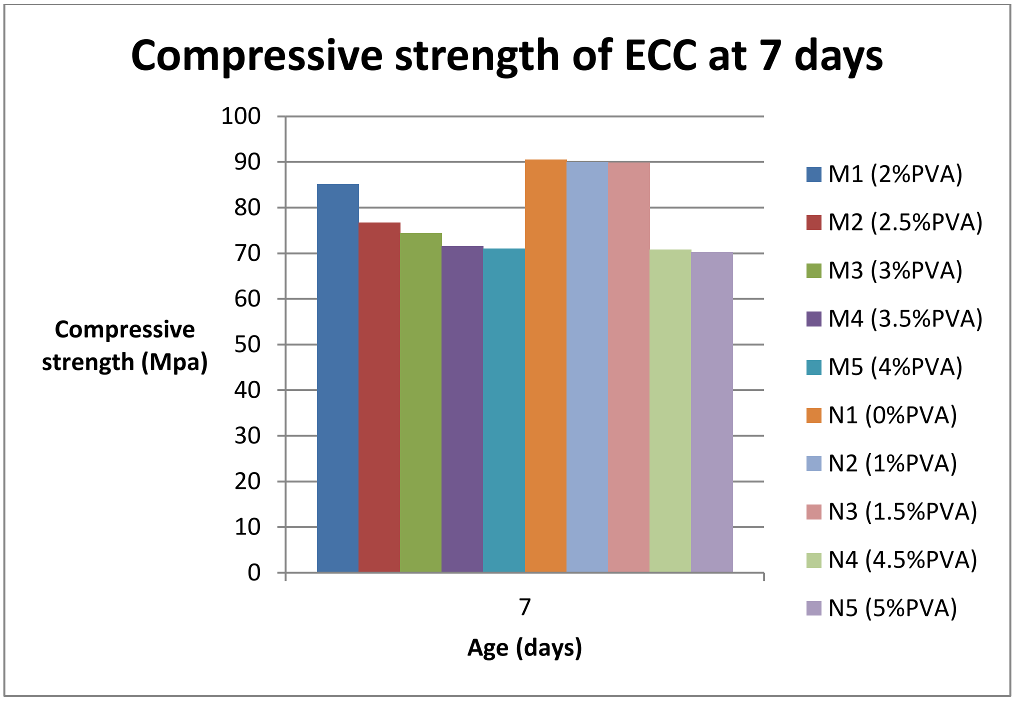


Figure 4.3: Compressive strength of ECC at 7 days

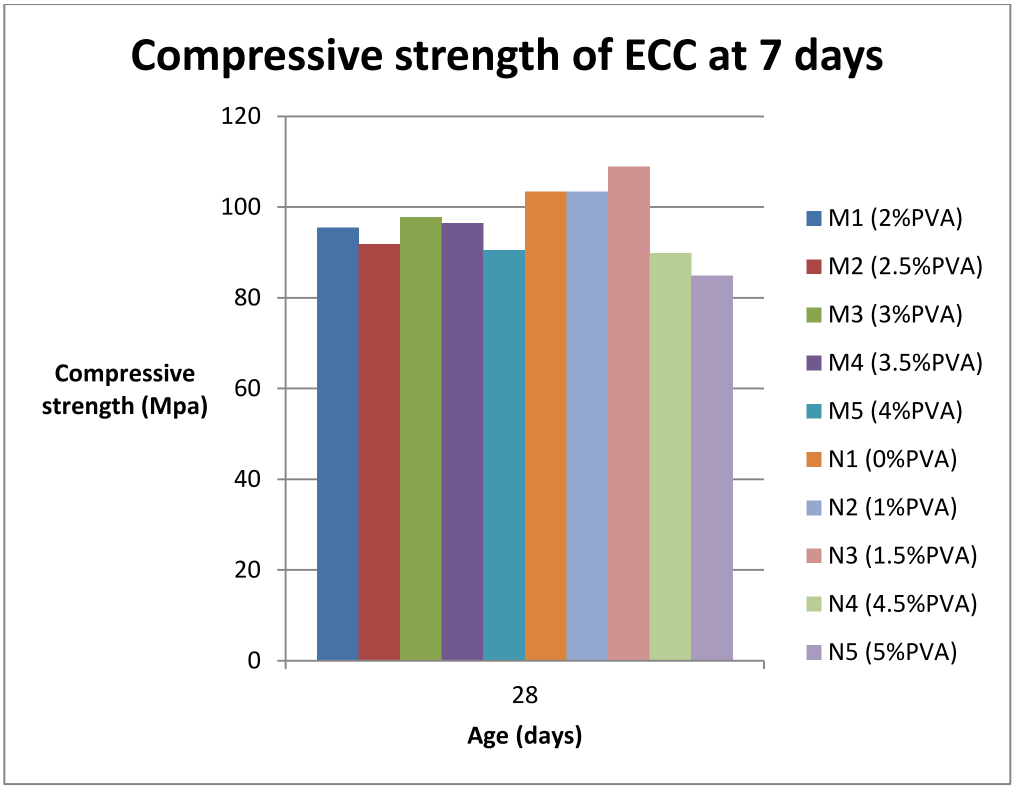


Figure 4.4: Compressive strength of ECC at 28 days

4.3. Bond Strength (Pull-Out Test)

Modes of failure

In total, pull-out tests are carried out on 35 specimens, 15 of the test specimens were for 12 mm reinforcing bars and 20 test specimens were for 16 mm bar size. In this pull-out test conducted, failure occurred in the three principal regions: in the concrete, at the steel–concrete interface and failure of the steel rod. All the test samples with 12 mm embedded reinforcement bars failed in the bars. For the 16 mm diameter embedded steel, most of the failures are shearing pullout failure without splitting in the PVA-ECC cylinders (Failure 4.5) except for mixes N_1, N_4 and N_5. Mix N_1 failed by breakage of the PVA-ECC cylinders as shown in Figure 4.6 (L). Failure of reinforcing bars occurred for mixes N_4 and N_5 as indicated in Figure 4.6 (R).

Figure 4.5: Common Failure Modes observed during the pull-out test in this project

Figure 4.6: Splitting failure of cylinder for N1 (L) and failure in reinforcing bar (R).

From the test results, the bond stress between reinforcing bar and concrete and the bond stress–slip diagrams can be obtained. The mean bond stress (MPa) is calculated as follows:

$$\tau = \frac{p}{\pi d l}$$

Where

- **p** refers to the applied load (N),
- **d** is the diameter of the bar (mm) and
- l is the embedment length of the reinforcing bar (mm).

l = 150 mm or ¾ h where h is the height of the cylinder in mm.

The mean bond stress determined as above is the ultimate bond strength and is defined as the bond stress corresponding to the ultimate load recorded during testing. The mean values of the experimentally determined ultimate bond strengths for the different PVA-ECC mixes are as shown in Table 4.3. It has been found out that, bond strength between reinforcing steel and ECC increases with increase in PVA fiber contents. ECC cylinders without PVA have the lowest bond strength and the sample failed in such a way that it splits or breaks up into pieces. ECC cylinders with 1.0% to 4.0% PVA failed by pulling out of the steel from the cylinder while for ECC with 4.5% and 5.0% PVA content, the failure was on the reinforcing steel. The pull-out load–stroke curves for the specimens for the different mixes are as shown in (Figure 4.7). The results for the 12 mm diameter reinforcing bars are not discussed because all the 15 test specimens for 12 mm reinforcement bars showed a failure in the bars, and this gives the breaking strength of the bar instead of the bond strength between concrete and the reinforcing bar.

Table 4.3: Ultimate Bond Strength

Test Date		:	23/12/2013
Description of test Specimen		:	Cylindrical with diameter = 150mm and height = 300mm
Description of cast-in steel		:	12 mm reinforcement bar, embedded length = 150 mm
Detail of curing		:	Moist curing until the test date
Age at time of test		:	28 days
Surface Condition at time of test		:	Saturated Surface Dry
Mix ID	Maximum Load, P (KN)		Ultimate Bond Stress
M1	106.996		1513.075
M1	113.407		1603.735
M2	116.265		1644.152
M2	88.826		1256.125
M3	118.755		1679.364
M3	123.823		1751.032
M4	114.148		1614.214
M4	125.94		1780.97
M5	121.731		1721.448
M5	109.338		1546.194
N1	107.433		1519.255
N1	68.939		974.8949
N2	89.535		1266.152
N2	104.622		1479.503
N3	126.975		1795.606
N3	117.615		1663.242
N4	135.751		1919.711
N4	134.672		1904.453
N5	121.731		1721.448
N5	132.058		1867.487

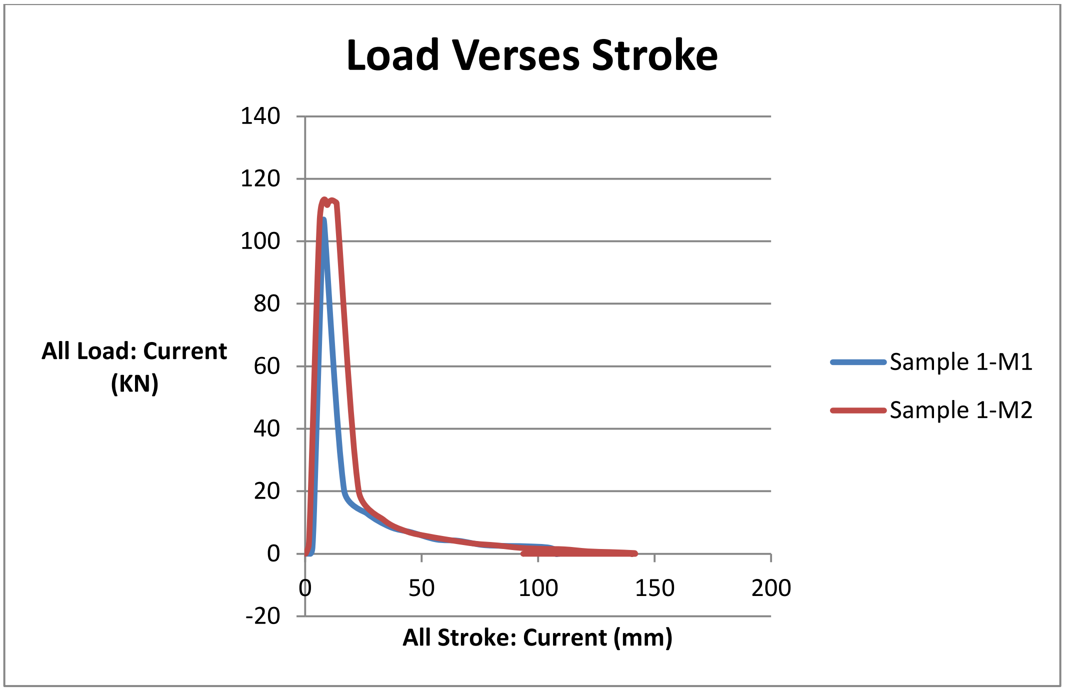


Figure 4.7(a): Pull-out load–Stroke curves for 16 mm diameter cast-in reinforcing bars with 2.0% PVA

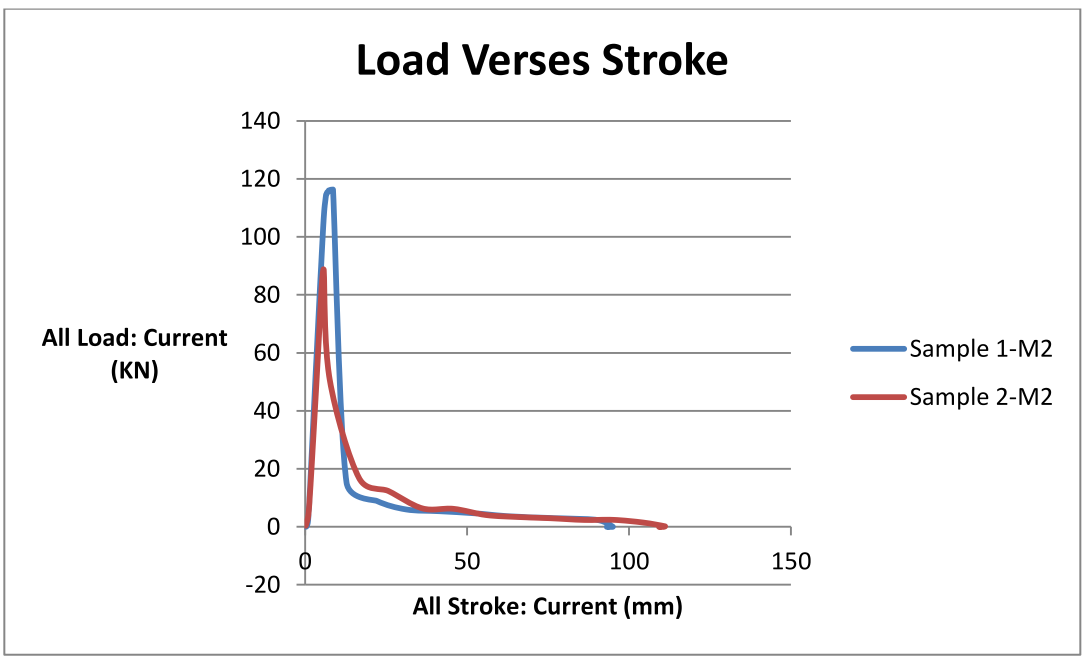


Figure 4.7(b): Pull-out load–Stroke curves for 16 mm diameter cast-in reinforcing bars with 2.5% PVA

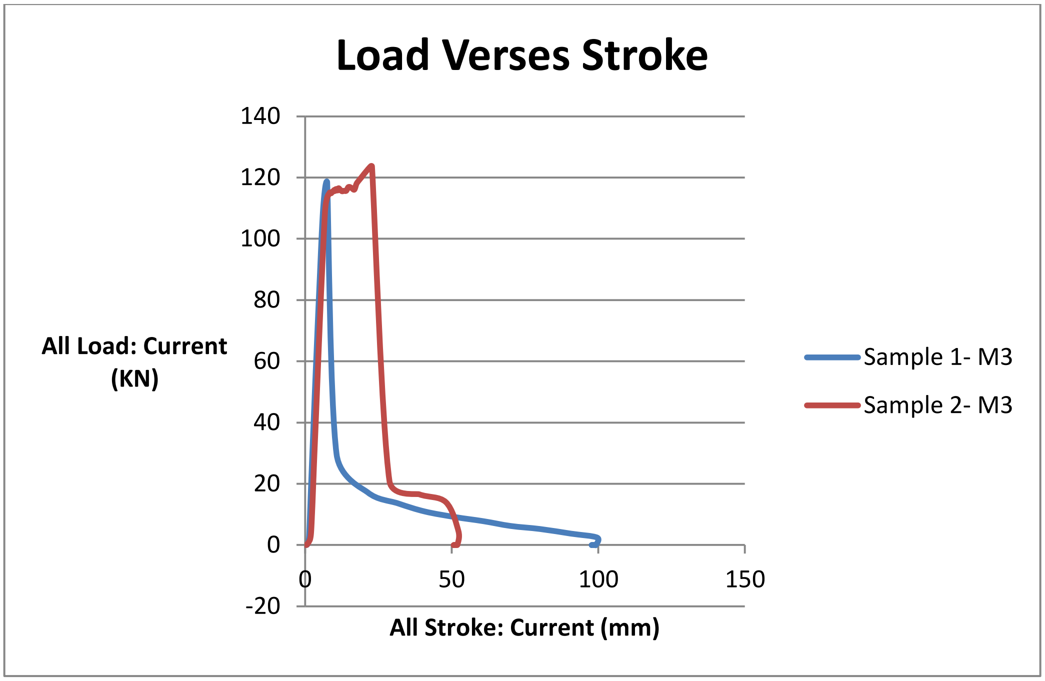


Figure 4.7(c): Pull-out load–Stroke curves for 16 mm diameter cast-in reinforcing bars with 3.0% PVA

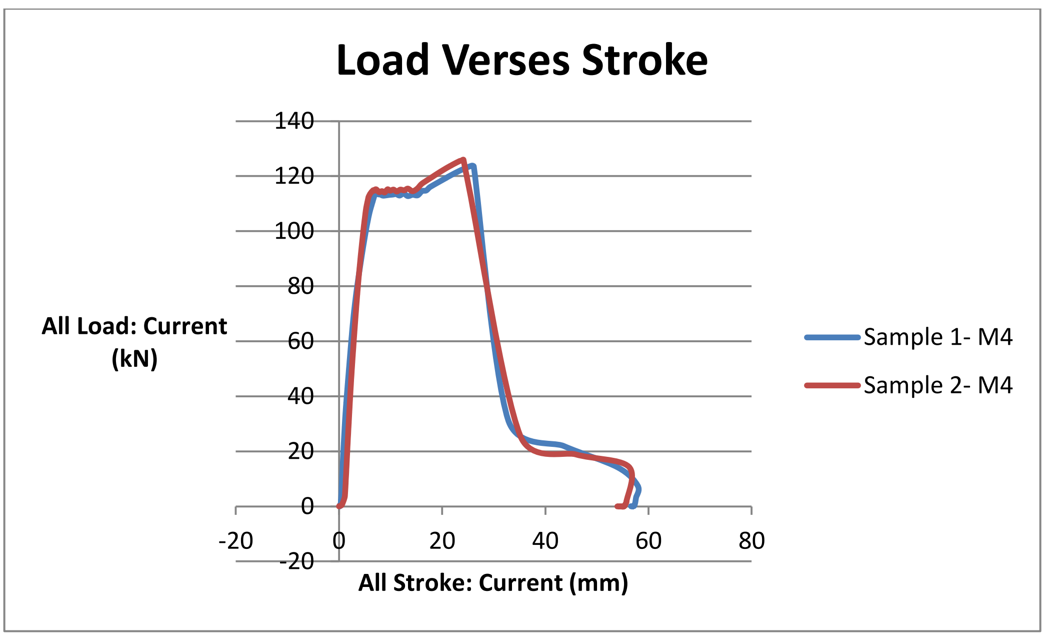


Figure 4.7(d): Pull-out load–Stroke curves for 16 mm diameter cast-in reinforcing bars with 3.5% PVA

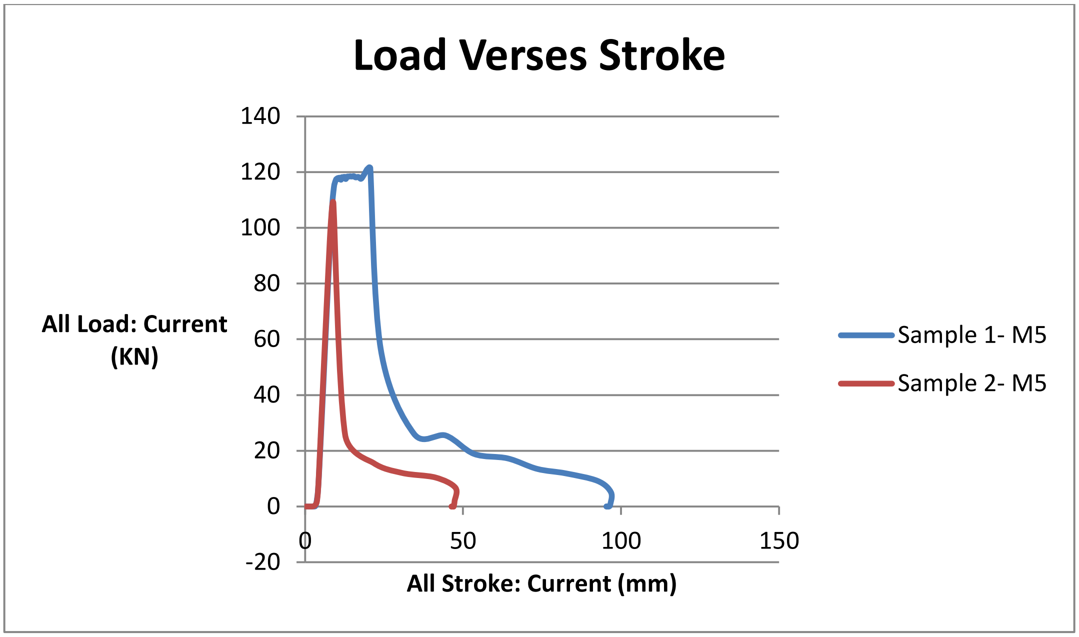


Figure 4.7(e): Pull-out load–Stroke curves for 16 mm diameter cast-in reinforcing bars with 4.0% PVA

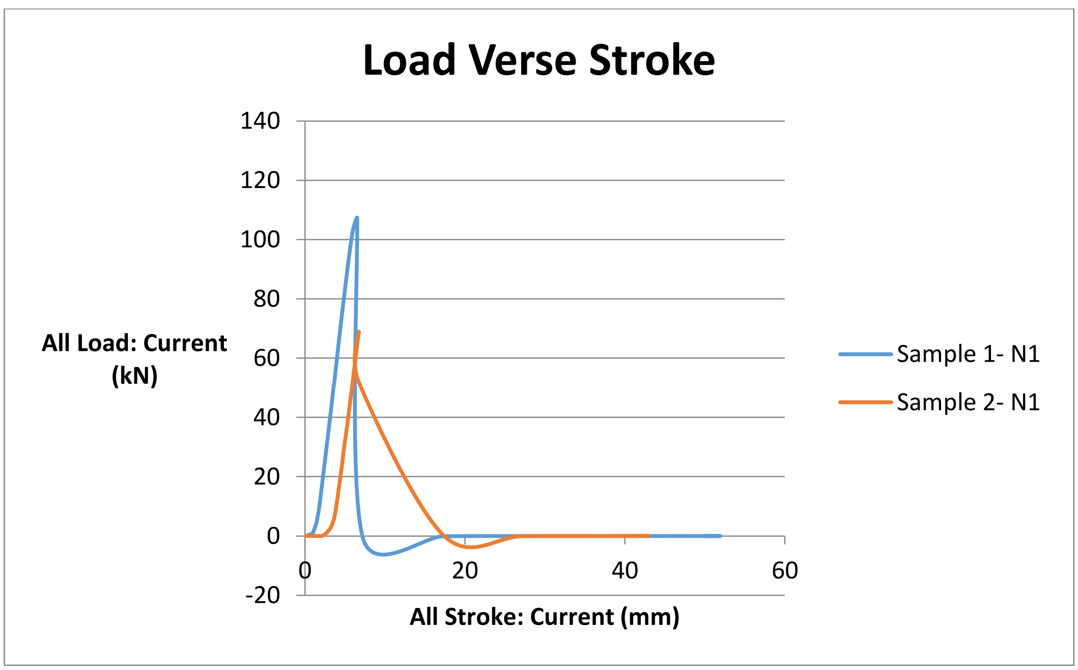


Figure 4.7(f): Pull-out load–Stroke curves for 16 mm diameter cast-in reinforcing bars with 0.0% PVA

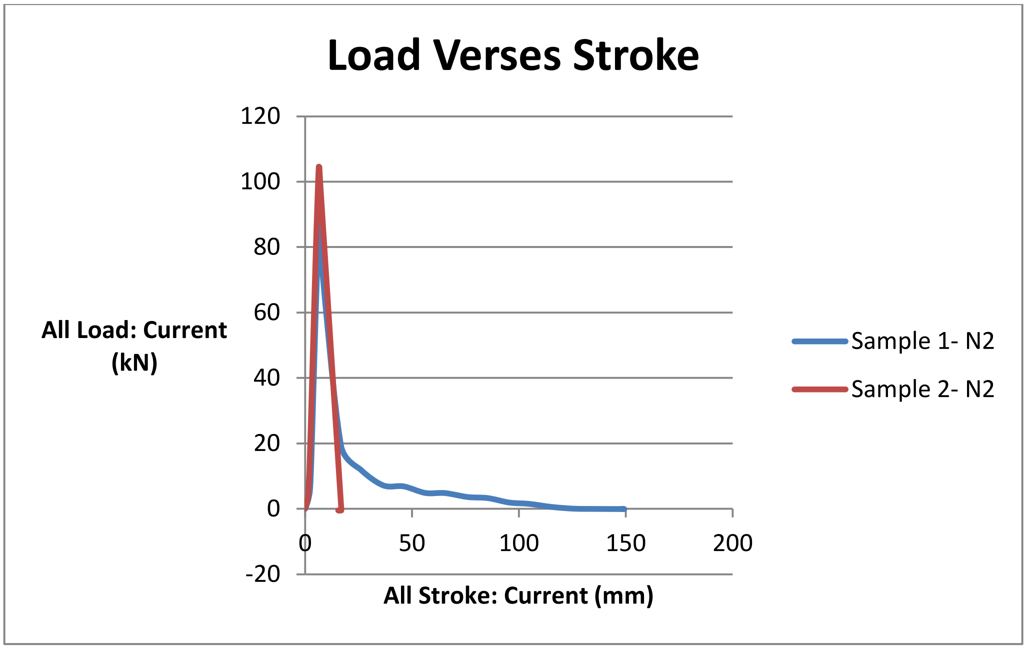


Figure 4.7(g): Pull-out load–Stroke curves for 16 mm diameter cast-in reinforcing bars with 1.0% PVA

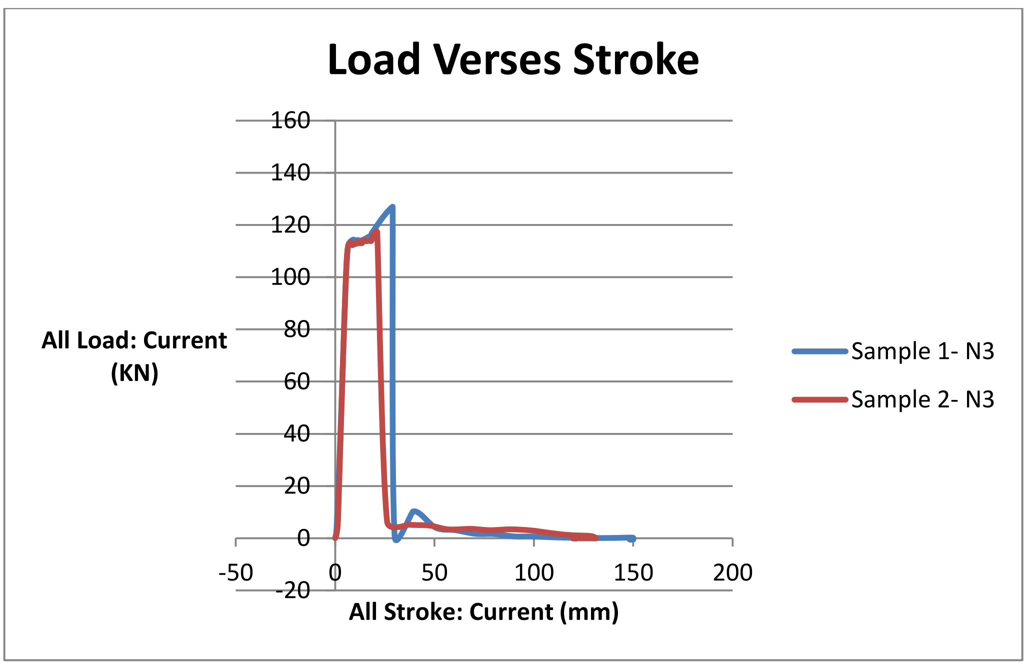


Figure 4.7(h): Pull-out load–Stroke curves for 16 mm diameter cast-in reinforcing bars with 1.5% PVA

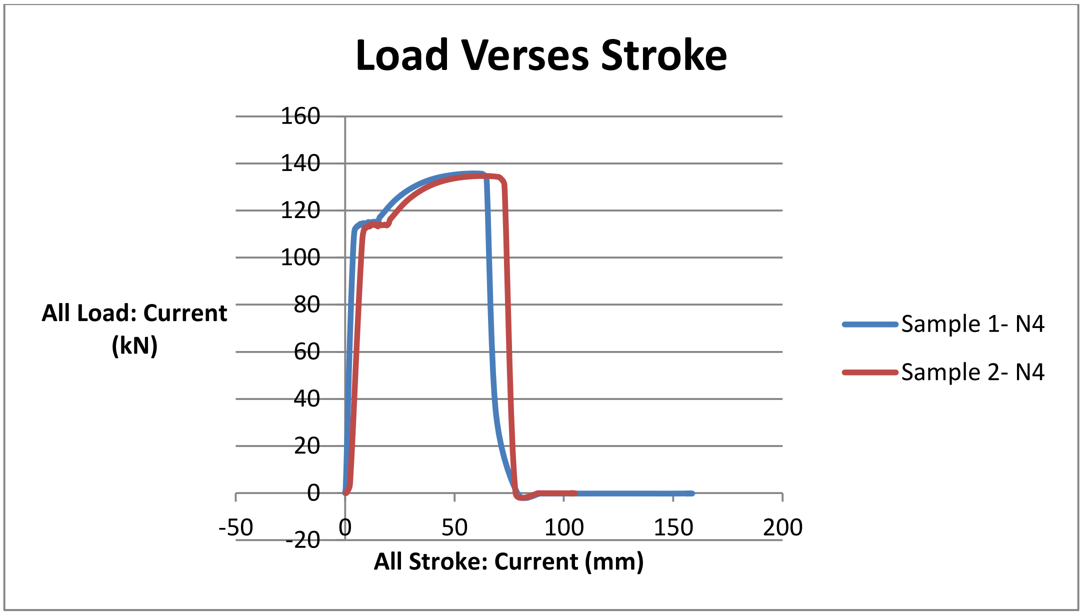


Figure 4.7(i): Pull-out load–Stroke curves for 16 mm diameter cast-in reinforcing bars with 4.5% PVA

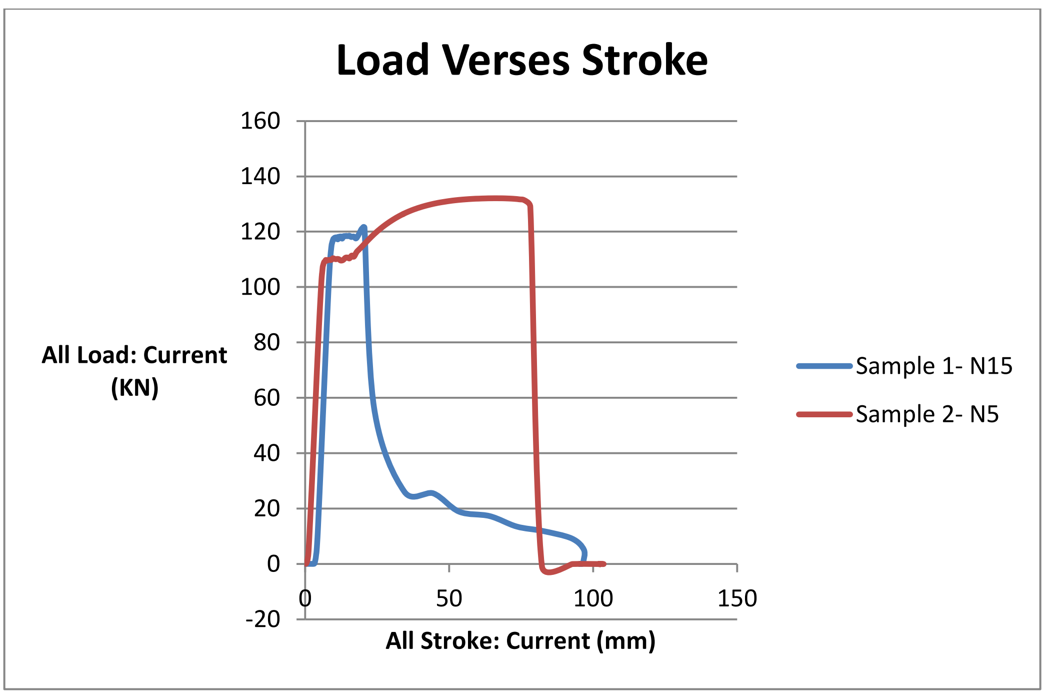


Figure 4.7(j): Pull-out load–Stroke curves for 16 mm diameter cast-in reinforcing bars with 5.0% PVA

Bond Behavior of ECC

As shown in Figure 4.8(a), the bond behavior for the 0.0% and 1.0% PVA consists of a sharply ascending stage, a sudden splitting of the ECC cylinder at the maximum pull-out force and then a sharp descending stage. However, the bond behavior of the ECC and reinforcement bars cast in it at higher PVA contents (1.5% - 4.0%) consists of four stages as shown in Figure 4.8(b-d).

The first stage of the bond stress-stroke behavior in these figures consists of a sharp ascending and linear up to about 70 – 80 % of the ultimate load. After this stage is the second stage of the bond stress-stroke behavior during which internal micro cracks develop and there is no significant increase in the bond stress as the stroke increases. The third stage consists of a further increase of bond stress until the pull-out load reached a peak value p_{max}. The last stage of the bond stress-stroke behavior is characterized by an increase in the stroke with a sudden decrease in the bond stress. The failure in this case is the spit cracking of the ECC cylinders, though the cylinders did not totally split like for the 0.0% and 1.0% PVA. For the highest PVA contents (4.0% and 5.0%), the bond-stroke behavior is similar to that of the intermediate (higher) PVA contents except that the failure occurred by the breakage of the steel bar as shown in Figure 4.8(e).

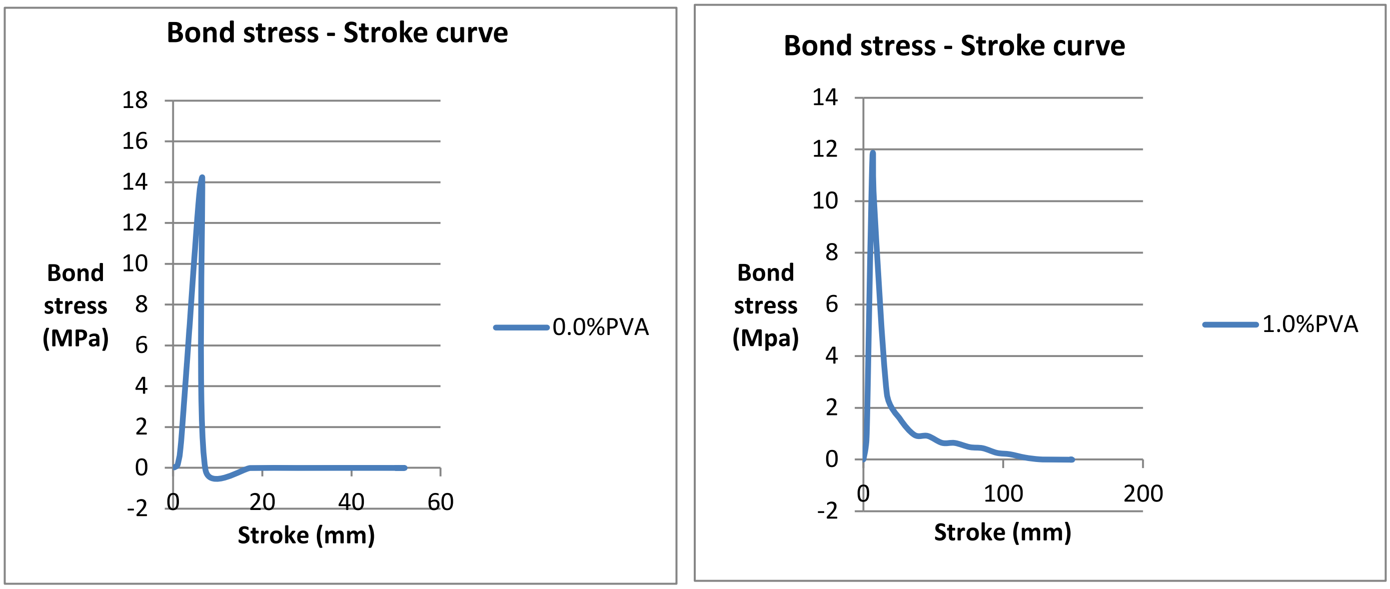


Figure 4.8(a): Bond stress – Stroke curves for 0.0% and 1.0% PVA

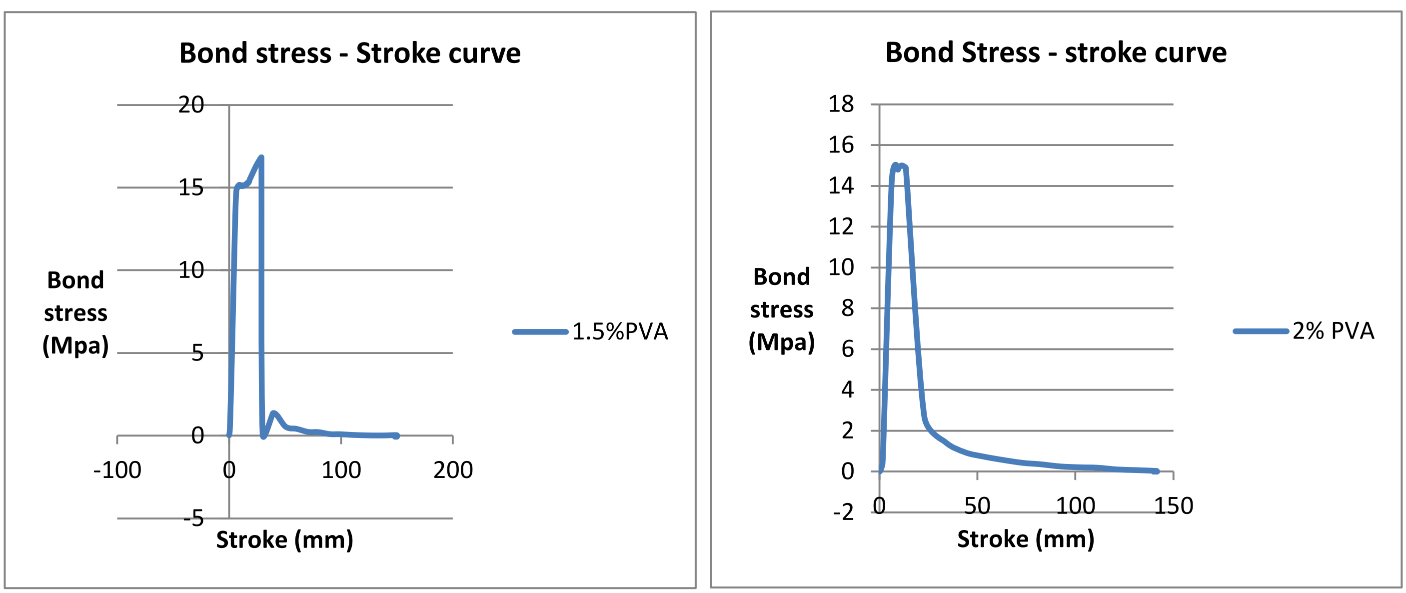


Figure 4.8(b): Bond stress – Stroke curves for 1.5% and 2.0% PVA

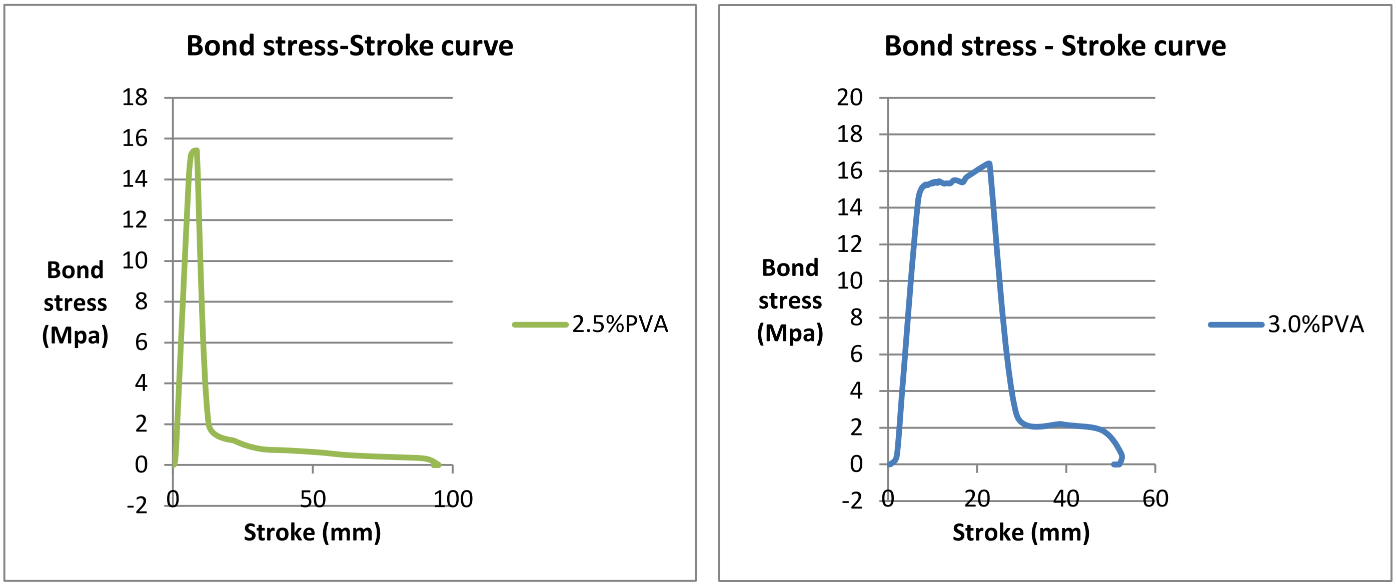


Figure 4.8(c): Bond stress – Stroke curves for 2.5% and 3.0% PVA

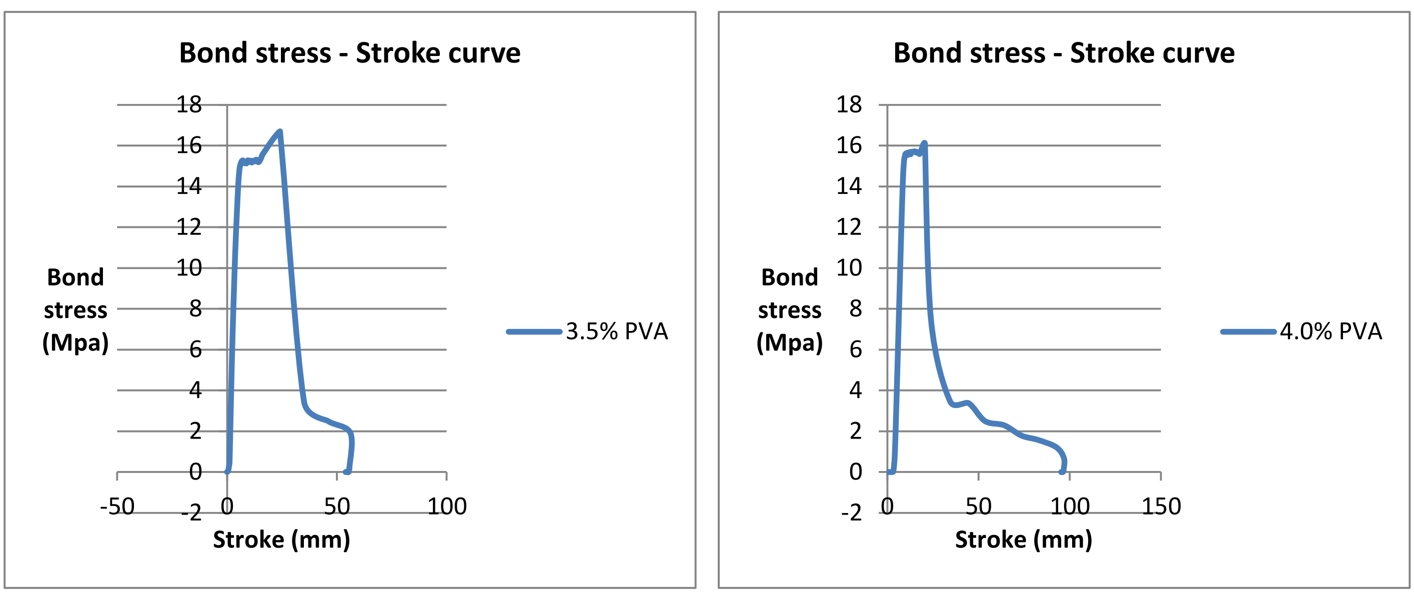
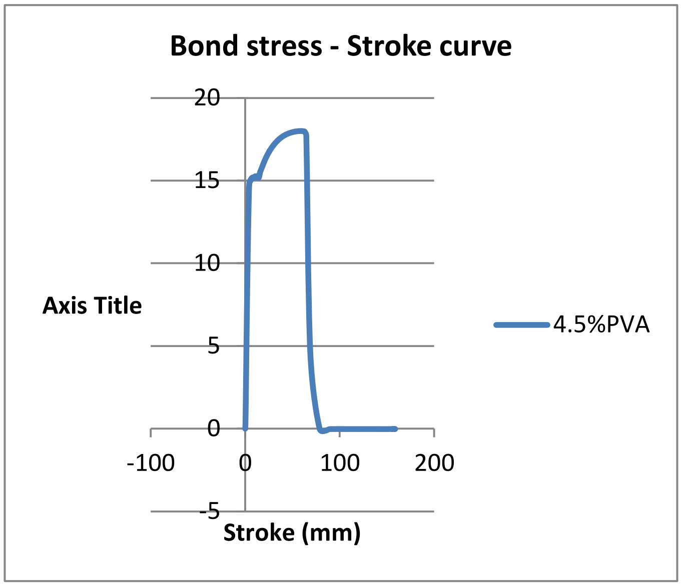


Figure 4.8(d): Bond stress – Stroke curves for 3.5% and 4.0% PVA



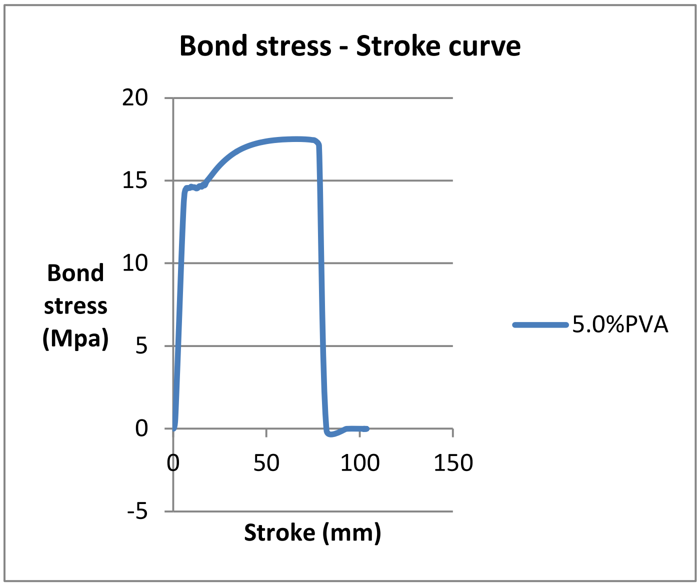


Figure 4.8(e): Bond stress – Stroke curves for 4.5% and 5.0% PVA

As shown in the Table 4.4 and in Figure 4.9, the bond strength between reinforcing steel and ECC increases with increase in PVA content.

Table 4.4: Ultimate Bond Strength

Mix ID	PVA (%)	Maximum Pull-Out Load, P (KN)	Ultimate Bond Strength (MPa)
M0	-	104.6	1.48
M1	1.0	107.4	1.52
M2	1.5	122.3	1.53
M3	2.0	110.2	1.56
M4	2.5	115.5	1.63
M5	3.0	116.3	1.64
M6	3.5	120.0	1.70
M7	4.0	121.3	1.72
M8	4.5	126.9	1.79
M9	5.0	135.2	1.91

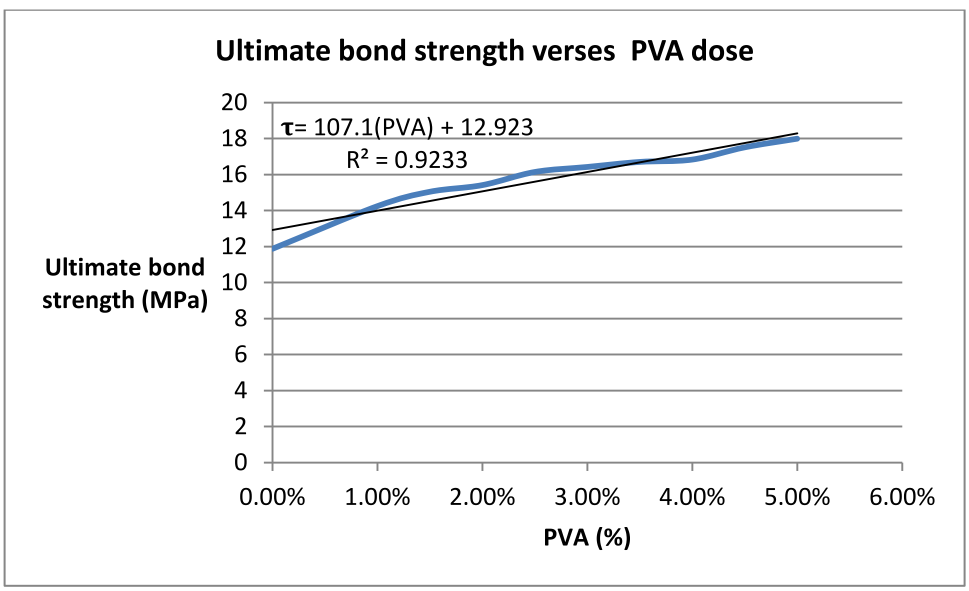


Figure 4.9: A plot of the ultimate bond strength against PVA percentage

Modeling of the bond – stroke relationship

Numerical analysis of the ECC members necessitates the need for modeling of bond behavior at the steel ECC interface. A normalized bond-stroke relationship (Figure 4.10 a-e) as shown in Equation 2 is proposed in terms of the following dimensions [17]

$$\bar{\tau} = \frac{\tau}{\tau_{max}}, \quad \bar{s} = \frac{s}{s_{max}}, \quad \text{..........} \quad (2)$$

Where s_{max} is the slip corresponding to peak bond stress τ_{max}

The ascending and the descending branches of the bond–stroke relationship have been modeled by suitably modifying the constants *a* and *b* in the following constitutive equations (3) for normal-strength concrete proposed by Harajli [18] and Guo [19] respectively, where *a* is a function of the slope of the ascending branch and *b* is related to the area under the descending branch of the stress–strain curve.

$$\bar{\tau} = \begin{cases} (\bar{s})^{a} & \bar{s} \leqslant 1, \\ \frac{\bar{s}}{b(\bar{s}-1)^2+\bar{s}} & \bar{s} > 1, \end{cases} \quad \text{..........} \quad (3)$$

Comparison of the predicted bond-stroke relationship with the measured one shows a good correlation between the two for ECC.

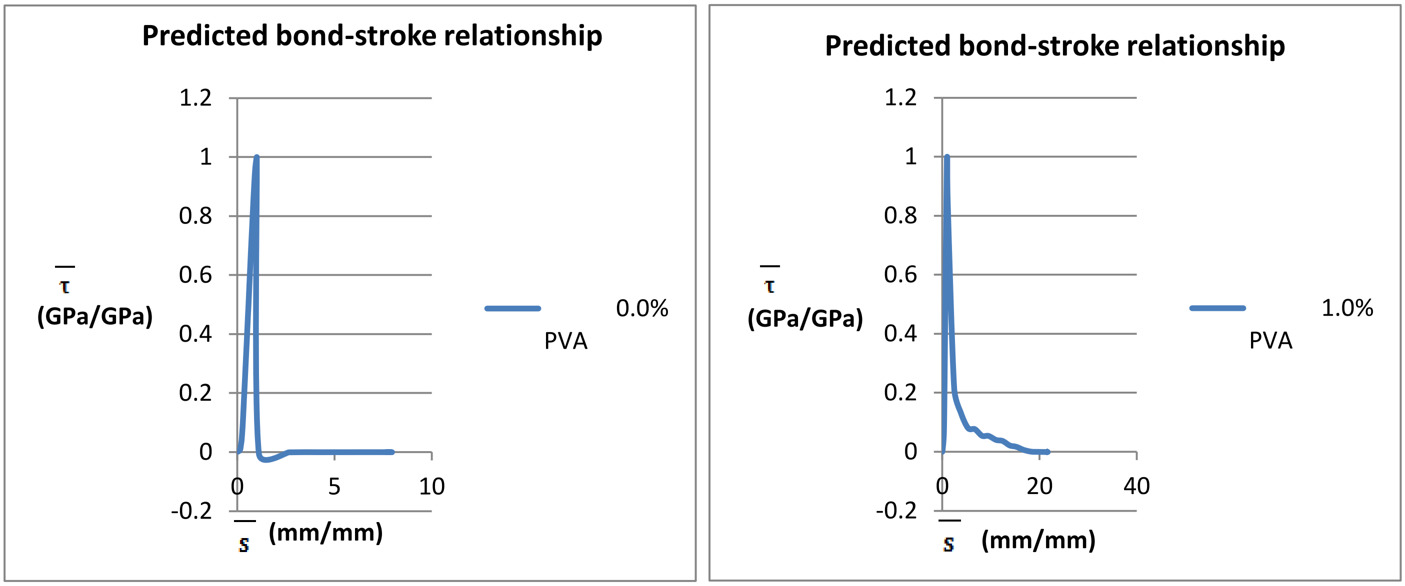


Figure 4.10(a): Predicted bond stress – Stroke curves for 0.0% and 1.0% PVA

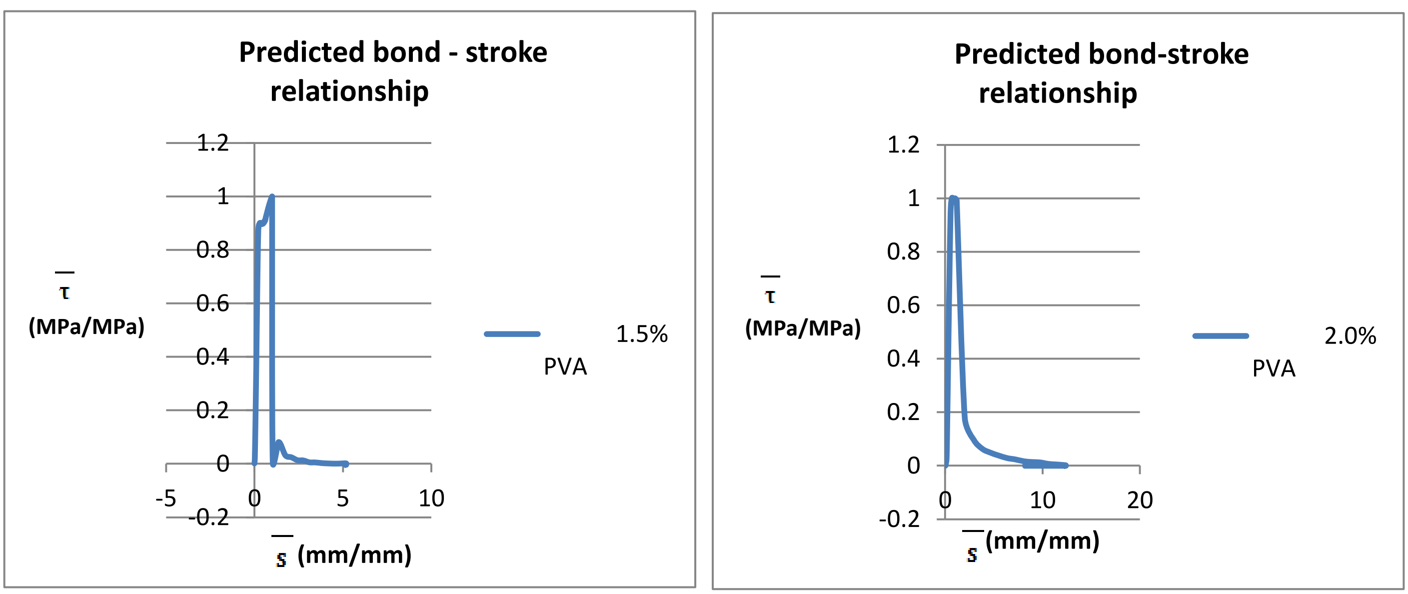


Figure 4.10(b): Predicted bond stress – Stroke curves for 1.5% and 2.0% PVA

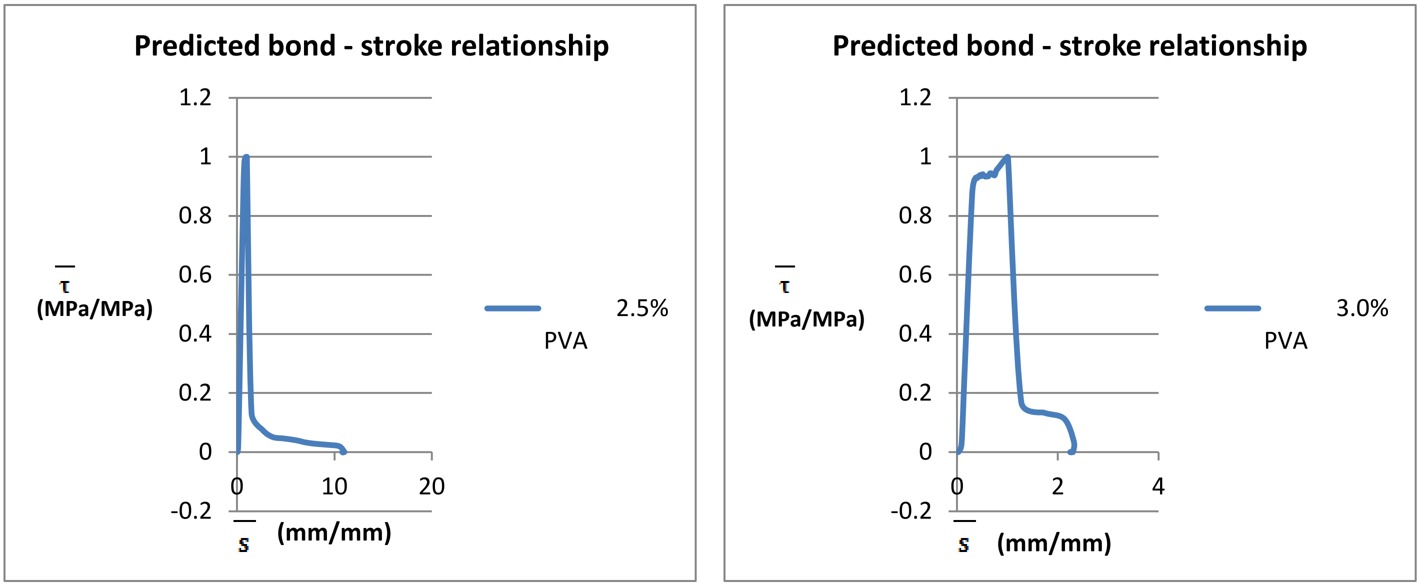


Figure 4.10(c): Predicted bond stress – Stroke curves for 2.5% and 3.0% PVA

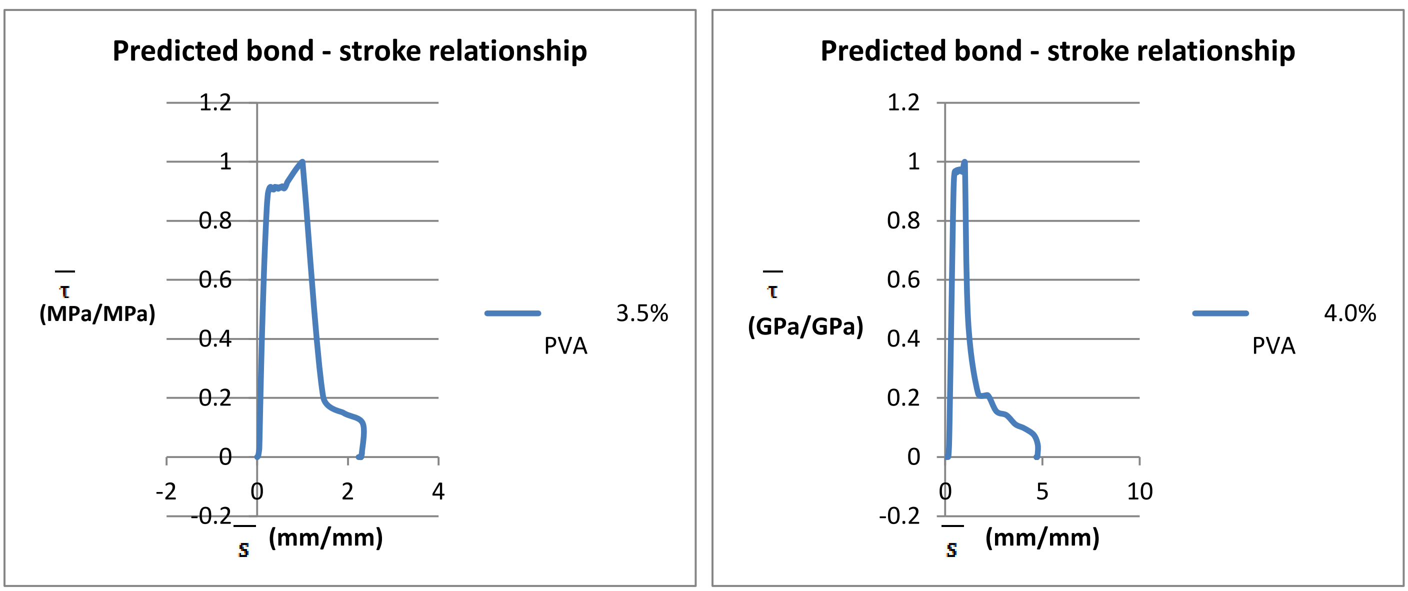


Figure 4.10(d): Predicted bond stress – Stroke curves for 3.5% and 4.0% PVA

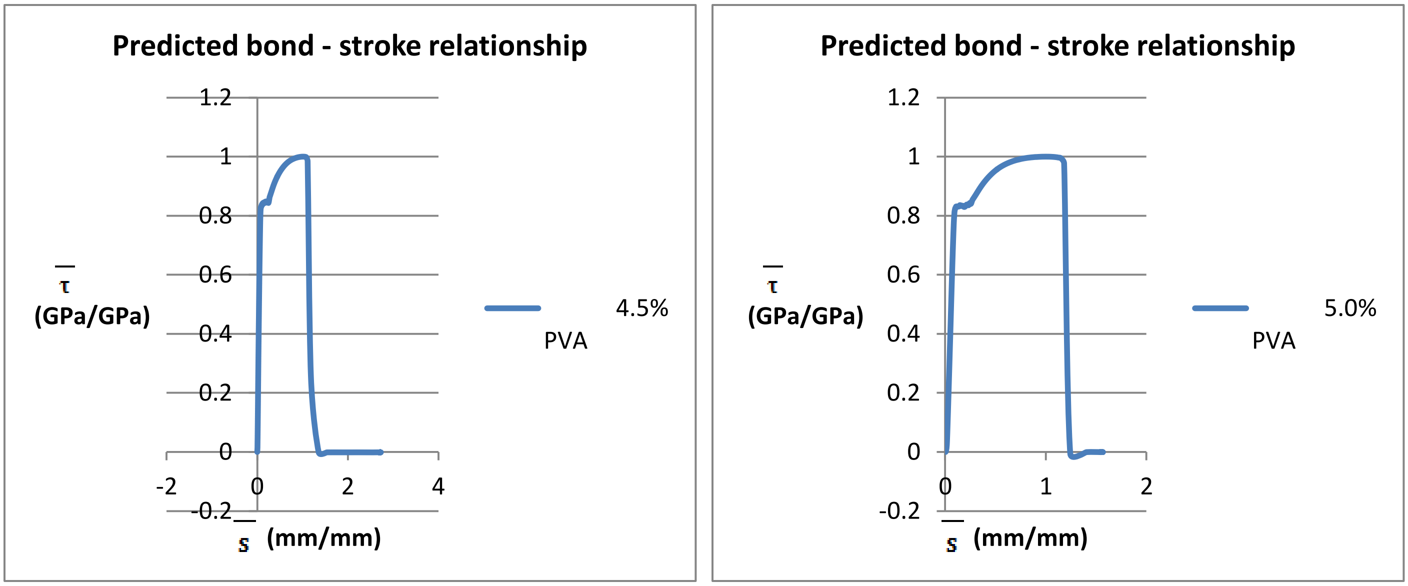


Figure 4.10(e): Predicted bond stress – Stroke curves for 4.5% and 5.0% PVA

4.4. Modulus of Elasticity

Figure 4.6 summarizes the values of modulus of elasticity obtained using Non Destructive Testing (NDT) method. The test result shows that the modulus of elasticity of PVA-ECC increases with increasing PVA fiber content but a very high percentage of fiber, the modulus of elasticity is lower. This could be due to the reduction in workability at high fiber content resulting from the difficulties to ensure uniform distribution of fibers.

Figure 4.6: Testing for Modulus of Elasticity using the PUNDIT ultrasonic concrete tester

Specimen Describtion	:	Cylindrical, 150mm diameter and 300 mm height
Path Length	:	0.30 m
Correction	:	100%
Poiss. Rat.	:	0.2

Mix ID	**Average Mass (Kg)**	**Average Density (Kg/m3)**	**Average Modulus of Elasticity (Gpa)**
M1	11.68	2203.77	39.5
M2	11.74	2215.09	39.6
M3	11.8	2226.42	40.5
M4	11.94	2252.83	41.2
M5	11.82	2230.19	40.2
N1	12.38	2335.85	41.6
N2	12.38	2335.85	41.7
N3	12.32	2324.53	42.8
N4	12.16	2294.34	38.3
N5	11.98	2260.38	40.5

Figure 4.8 is a plot of modulus of elasticity against the compressive strength of the developed PVA-ECC. Modulus of elasticity can be used as an indirect method to determine the compressive strength of concrete. According to ACI 318-02, the modulus of elasticity can be determined from compressive strength using the relationship below:

$E_c = 4700f_c^{1/2}$

Where:

E_c is the modulus of elasticity in (MPa) and

f_c is the compressive strength in (Mpa)

As shown in Figure 4.8, the equation of the line of best fit representing the relationship between modulus elasticity and compressive strength self-consolidating PVA fiber reinforced ECC is given as:

$E_{ECC} = 0.1354f_c + 27.551$ for linear regression (Figure 4.8a) or

$E_{ECC} = 9.6591f_c^{\ 0.3144}$ for power regression (Figure 4.8b).

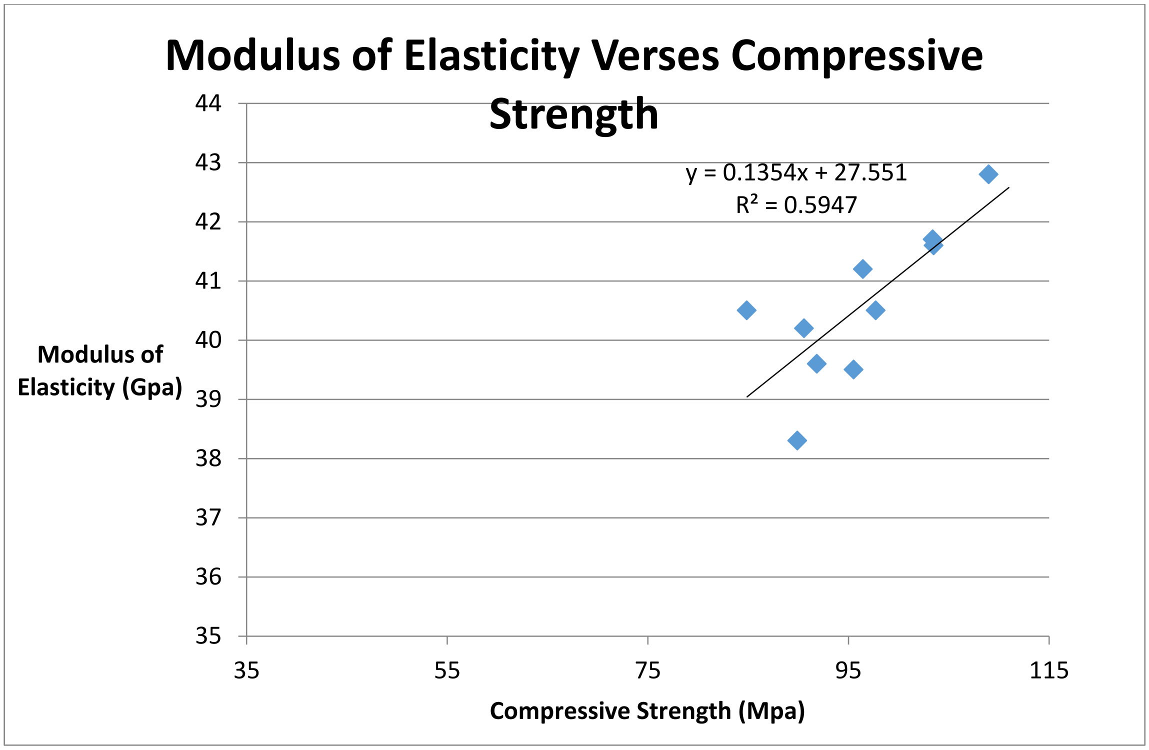


Figure 4.8a: A plot of modulus of elasticity against the compressive strength

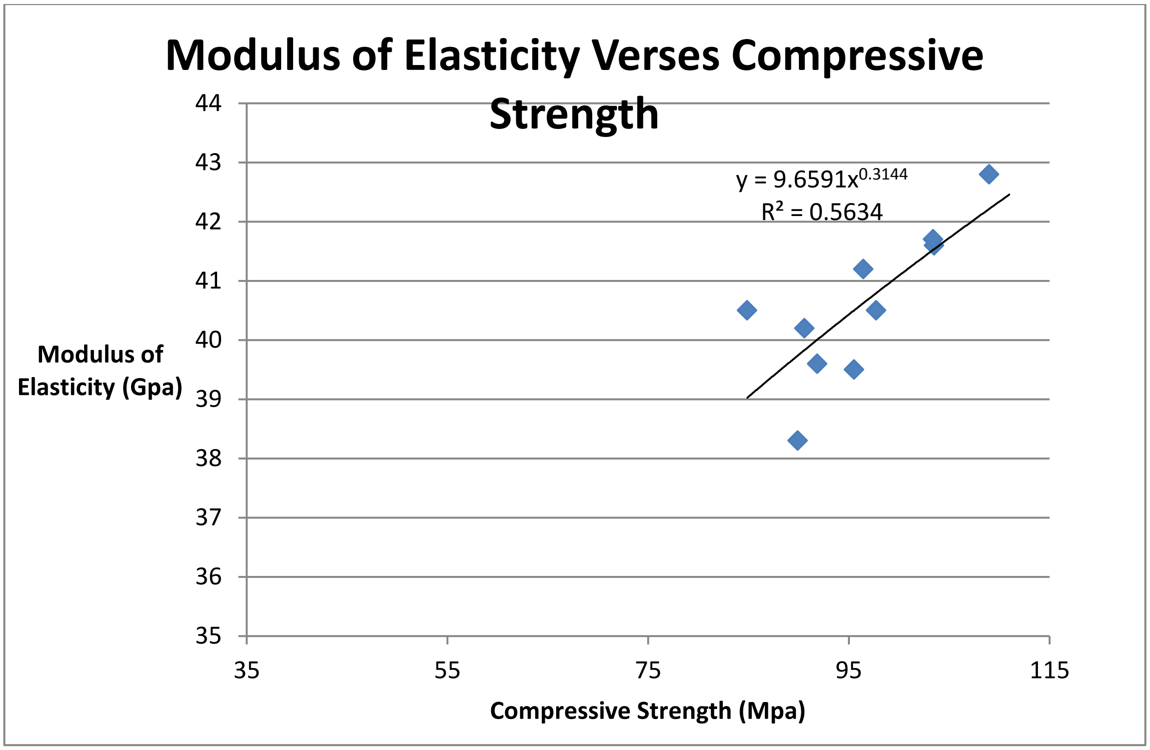


Figure 4.8b: A plot of modulus of elasticity against the compressive strength

CHAPTER 5: CONCLUSIONS

Comparisons of the values of slump flow, V-funnel and L-box measured in this project (Table 4.1) with the standard requirements for SCC in Table 3.6 shows that:

a) The all the measured values of the slump spread fall within the minimum (650 mm) and maximum (800 mm) requirement for slump spread of SCC except for M_1 which exceeds the maximum requirement.
b) The values of T50 obtained are all in the range of 2 – 5 seconds required for SCC.
c) The required V-funnel flow time for SCC as shown in Table 3.6 is 6 – 12 seconds and the ones obtained in this project all fall in this range.
d) The requirement for L-box (h_2/h_1) which is 0.8 – 1.0 have also been satisfied by all the mixes as shown in Table 4.1.

It can therefore, be concluded that the first objective of this research which is to develop polyvinyl alcohol (PVA) fiber reinforced self-consolidating Engineered Cementitious Composites (ECC) has been achieved. The test results for the fresh PVA-ECC show that slump spread decreases with increase in the content of PVA when other compositions remain constant. Furthermore, the V-Funnel flow decreases with increase in PVA content. The workability of the PVA-ECC is reduced at high percentage of PVA as illustrated by the plot of slump flow against PVA dosage (Figure 4.1). The slump flow is the maximum without PVA and as PVA dose increases, the slump spread decreases. The further increase of slump spread at 2.0% PVA is due to an increase in the amount of superplasticizer from 4.5 % to 9.5%.

The bond strength between reinforcing steel and ECC increases with increase in PVA fiber contents. ECC cylinders without PVA have the lowest bond strength and the sample failed in such a way that it splits or breaks up into pieces. ECC cylinders with 1.0% to 4.0% PVA failed by pulling out of the steel from the cylinder while for ECC with 4.5% and 5.0% PVA content, the failure was on the reinforcing steel which clearly shows that bond strength of PVA-ECC increases as the fiber contents increases.

The modulus of elasticity of PVA-ECC increases with increasing PVA fiber content. Modulus of elasticity also increases as the compressive strength of PVA-ECC increases.

REFERENCES

1. M. L. Gambhir (2004). *Concrete technology*. Third Ed. Tata McGraw-Hill Publishing Company limited, New Delhi
2. M. S. Shetty (2001). *Concrete technology*. Theory and Practice, fifth ed. Chand & Company Ltd, 3761, Ram Nagar, New Delhi-110055
3. S. H. Kosmatka & W. C. Panarese (1994). *Design and Control of Concrete Mixtures.* Third Ed, Portland cement Association, 5420 Old Orchard Road, Skokie, Illinois 60077-1083
4. V.C. Li, et al, (2002). *Interface tailoring for strain-hardening polyvinyl alcohol-engineered cementitious composites (PVA-ECC).* ACI Mater J, Vol. 99, Issue 5, pp. 463–472
5. A. S. F. Uddin, and M. Hirozo, (2007). *A review on durability properties of strain hardening fiber reinforced cementitious composites (SHFRCC).* Cement and Concrete Composites, Vol. 29, Issue 5, pp. 365–376.
6. S. H. Kosmatka & W. C. Panarese (1994). *Design and Control of Concrete Mixtures.* Third Ed, Portland cement Association, 5420 Old Orchard Road, Skokie, Illinois 60077-1083

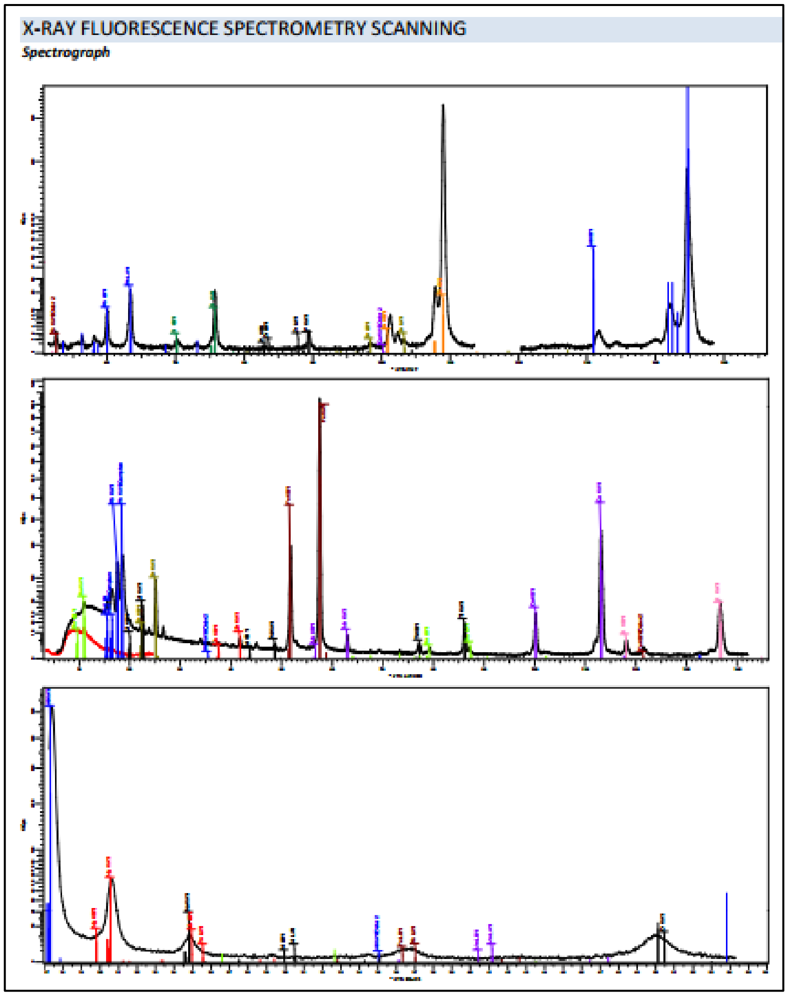
7. Zhou et al, (2012). *Improved fiber distribution and mechanical properties of engineered cementitious composites by adjusting the mixing sequence*. Cement & Concrete Composites Vol. 32, pp. 342-348
8. M. Maalej, T. Hashida & V.C. Li, (1995). *Effect of fiber volume fraction on the off-crack plane energy in strain-hardening engineered cementitious composites*. J Am Ceram Soc 78(12):3369–3375
9. M.B. Weimann, V.C. Li (2003). *Drying shrinkage and crack width of ECC, Brittle Matrix Composites 7*, Warsaw, Poland; pp. 37–46
10. M. Li & V. C. Li, (2012). *Rheology, fiber dispersion, and robust properties of Engineered Cementitious Composites.* RILEM J Materials and Structures, pp. 1–16.

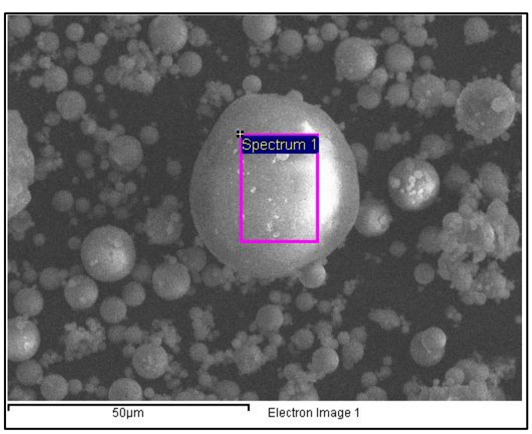
11. V.C. Li & T. Kanda, (1998). *Engineered Cementitious Composites for Structural Applications.* ASCE J. Materials in Civil Engineering, Vol. 10, No. 2, pp. 66-69
12. Huang, et al, (2013). *Development of green engineered cementitious composites using iron ore tailings as aggregates*. Construction and Building Materials, Vol. 44, pp. 757–764
13. M. Sahmaran & V.C. Li, (2008). *Durability of mechanically loaded engineered cementitious composites under highly alkaline environments.* Cement & Concrete Composites, Vol. 30, pp. 72–78
14. G.J. Parra-Montesinos, H.W. Reinhardt, and A.E. Naaman, (2012). *High Performance Fiber Reinforced Cement Composites 6: HPFRCC 6* (Edited). RILEM, Springer Dordrecht Heidelberg, London, New York.
15. R.F. Warner, et all, (1998). *Concrete Structures*. Addison Wesley Longman Australia Pty Limitted, South Melbourne 3205 Australia
16. A. F. Asl, S. Dilmaghani and H. Famili (2008). *Bond Strength of Reinforcement Steel in Self-Compacting Concrete.* International Journal of Civil Engineerng, Vol. 6, No. 1
17. ACI Committee 318, (2002). *Building Code Requirements for Structural Concrete* (ACI 318- 02) and commentary 318R-02), USA
18. P. Helincks, (2013). *Structural behaviour of powder-type self-compacting concrete: Bond performance and shear capacity.* Elsevier; Engineering Structures Vol. 48, pp. 121–132
19. L. Bouazaoui, and A. Li, (2008). *Analysis of steel/concrete interfacial shear stress by means of pull out test.* International Journal of Adhesion & Adhesives Vol. 28, pp. 101–108
20. Choi, et all, (2013). *Effect of steel wrapping jackets on the bond strength of concrete and the lateral performance of circular RC columns*. Engineering Structures Vol. 48, pp. 43–54
21. I.P. Sfikas and K.G. Trezos, (2013). *Effect of composition variations on bond properties of Self-Compacting Concrete specimens*. Construction and Building Materials Vol. 41, pp. 252–26

22. H. Yildirim and O. Sengul, 2011). *Modulus of elasticity of substandard and normal concretes. Construction and Building Materials,* Vol. 25, pp. 1645–1652
23. K.K. Sideris, P. Manita, and K. Sideris, (2004). *Estimation of ultimate modulus of elasticity and Poisson ratio of normal concrete.* Cement & Concrete Composites, Vol. 26, pp. 623–631
24. ASTM C469 / C469M – 10: *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*
25. M. Saridemir, (2013). *Effect of silica fume and ground pumice on compressive strength and modulus of elasticity of high strength concrete.* Construction and Building Materials Vol. 49, pp. 484–489
26. EN 12350, (2010). *Testing fresh concrete – Part 8: Self-compacting concrete – slump-flow test*
27. ASTM C1611, (2007). *Standard test method for slump flow of self-consolidating concrete.* Annual Book of ASTM Standards, Section 04, V04.02: Concrete Aggregate
28. EN 12350, (2010). *Testing fresh concrete Part 9: Self-compacting concrete – V-funnel test*
29. EN 12350, (2010). *Testing fresh concrete Part 10: Self-compacting concrete – L-box test*
30. BSI BS EN 12504-3, (2005). *Testing concrete in structures Part 3: Determination of pull-out force*
31. EFNARC (2002). *Specification and Guidelines for Self-Compacting Concrete.* EFNARC, Association House, 99 West Street, Farnham, Surrey GU9 7EN, UK
32. RILEM, (1973). *Technical recommendations for the testing and use of construction materials:* RC6, bond test for reinforcing steel: 2. Pull-out test, materials and structures

Appendix 1: Spectrograph and Detected Elements in Samples of Fly Ash

Spectrograph 1

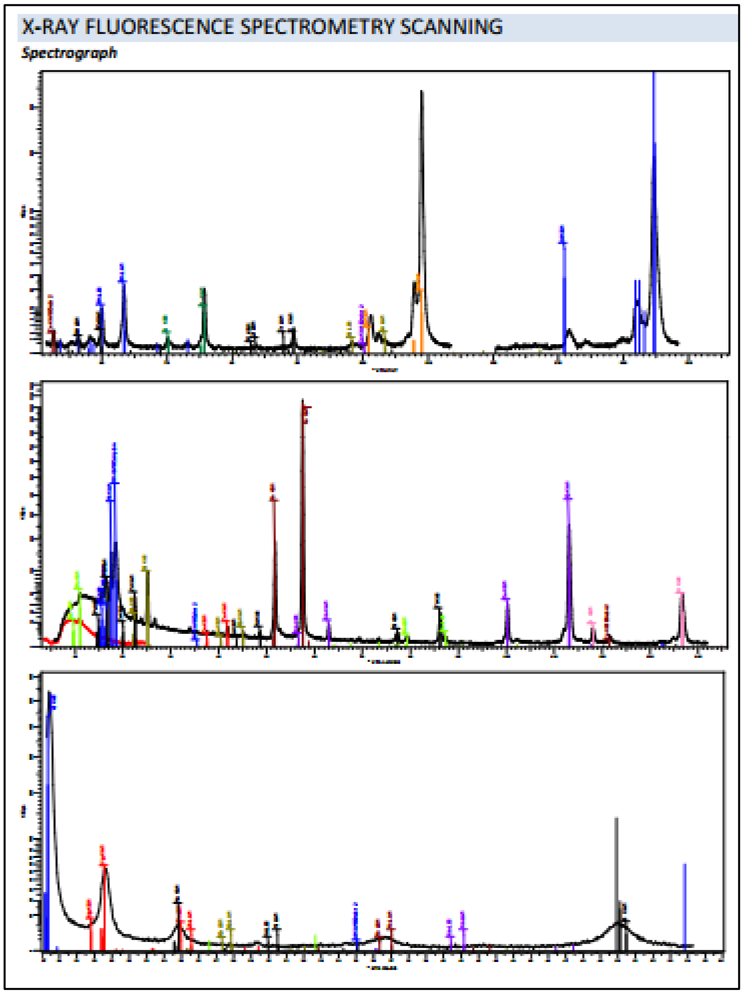




Detected Element in fly ash sample 1

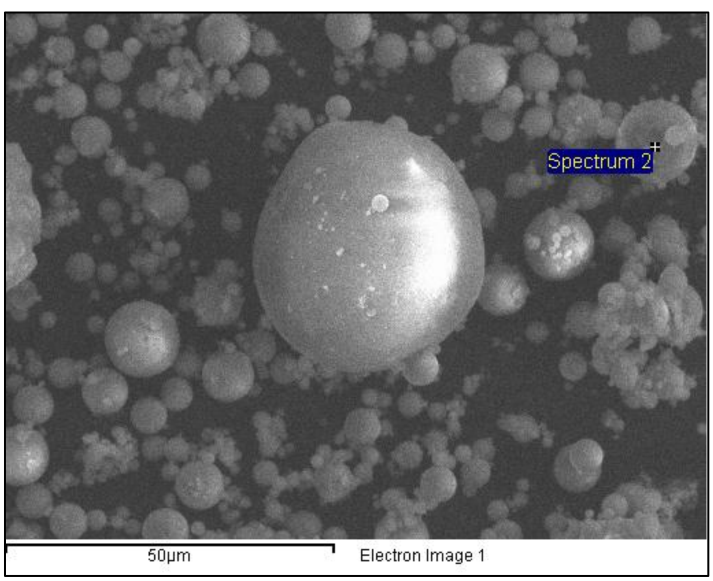
Formula	Concentration (%)
SiO_2	43.73
Al_2O_3	20.18
Fe_2O_3	12.37
CaO	11.14
MgO	3.75
K_2O	1.96
SO_3	1.45
Na_2O	0.93
TiO_2	0.88
P_2O_5	0.31
BaO	0.18
SrO	0.12
MnO	0.11
ZrO_2	0.04
ZnO	0.02
NiO	0.02
Cr_2O_3	0.01
CuO	0.01
Rb_2O	0.01
As_2O_3	65 PPM

Spectrograph 2

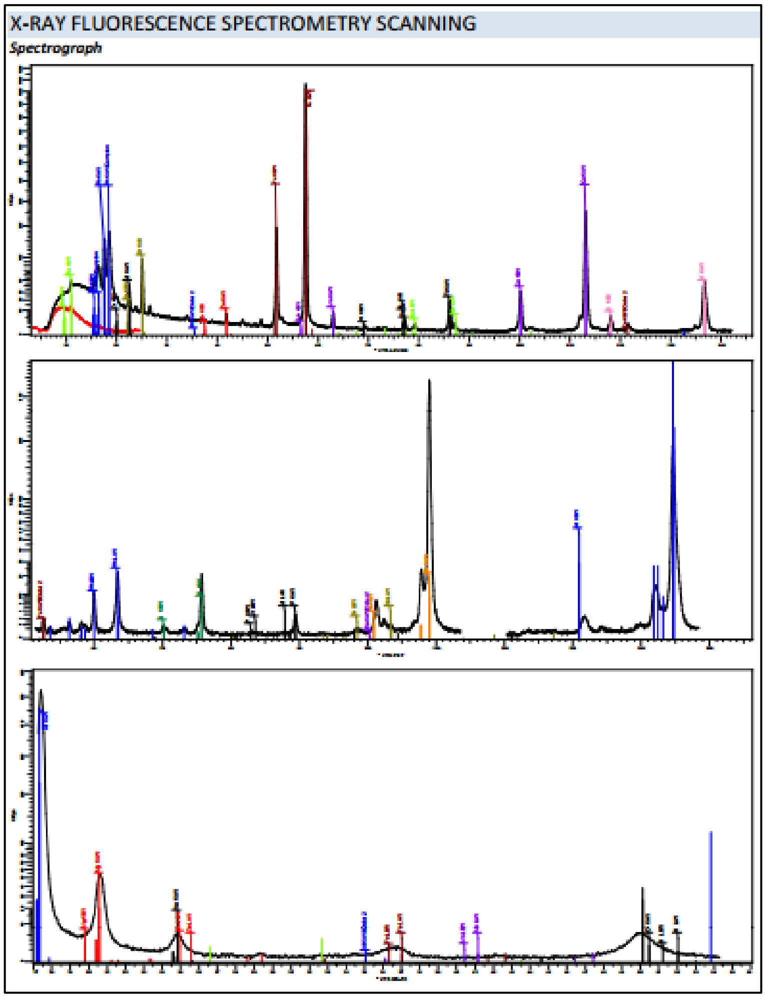


Detected Element in fly ash sample 2

Formula	Concentration (%)
SiO_2	42.69
Al_2O_3	20.81
Fe_2O_3	12.68
CaO	11.07
MgO	3.78
K_2O	1.94
SO_3	1.45
TiO_2	0.91
Na_2O	0.89
P_2O_5	0.34
BaO	0.19
SrO	0.12
MnO	0.11
ZrO_2	0.04
ZnO	0.02
NiO	0.02
CuO	0.01
Cr_2O_3	0.01
Pd	0.01
Rb_2O	83 PPM
As_2O_3	61 PPM
CoO	59 PMM

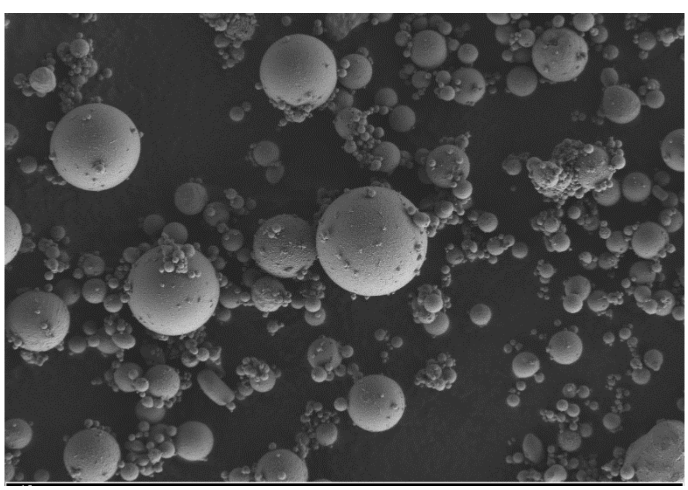


Spectrograph 3



Detected Element in fly ash sample 3

Formula	Concentration (%)
SiO_2	43.34
Al_2O_3	20.77
Fe_2O_3	12.41
CaO	11.13
MgO	3.75
K_2O	1.98
SO_3	1.45
TiO_2	0.95
Na_2O	0.88
P_2O_5	0.32
BaO	0.17
SrO	0.12
MnO	0.11
V_2O_5	0.04
ZrO_2	0.04
ZnO	0.02
CuO	0.01
Cr_2O_3	0.01
Rb_2O	95 PPM
As_2O_3	58 PPM
CoO	58 PMM



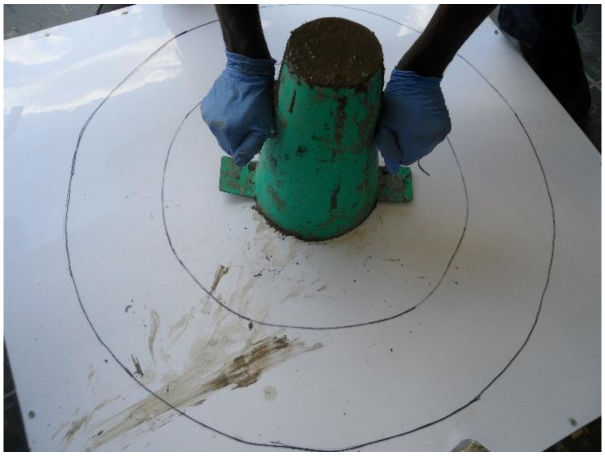
Appendix 2: Project Activities

Measuring quantities of constituent materials

Mixing the materials of ECC

Fresh ECC after Mixing

Fresh ECC ready for casting



Filling fresh ECC in Abraham's cone

Removing Abraham's cone

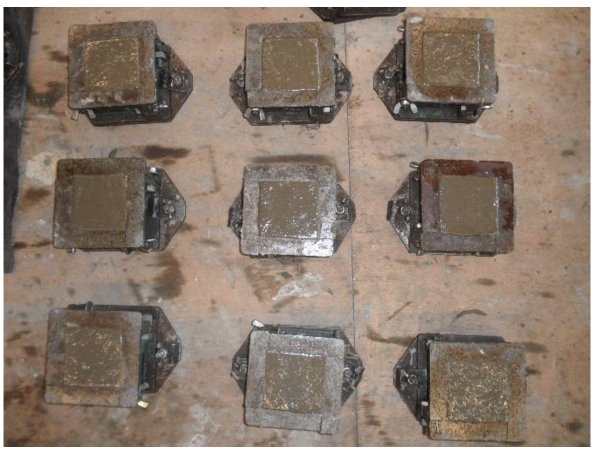
Measuring the slump flow

L – box testing

L – box testing continues

V- Funnel testing

Casting ECC cubes

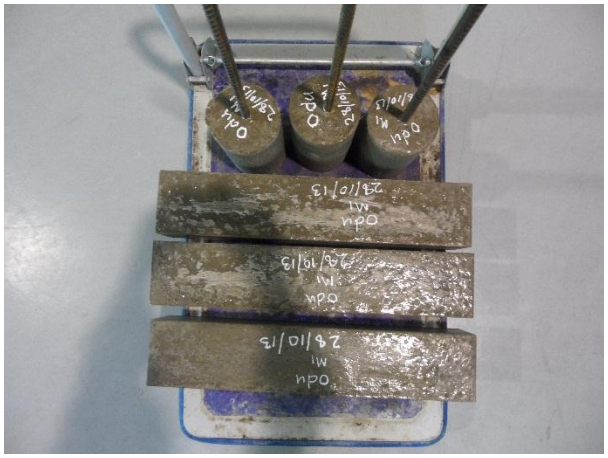


ECC cubes in the moulds

ECC cubes after removing from moulds

Casting ECC beams and cylinders

ECC beams and cylinders in moulds



ECC Beams and cylinders after removal from moulds

Curing of ECC Beams and cylinders after removal from moulds

Testing compressive strength of ECC cube **ECC cube after failure**